Development of Uniform Artificial Soil Deposition Techniques on Glass and Photovoltaic Coupons

by

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ABSTRACT

Soiling is one of the major environmental factors causing the negative performance of photovoltaic (PV) modules. Dust particles, air pollution particles, pollen, bird droppings and other industrial airborne particles are some natural sources that cause soiling. The thickness of soiling layer has a direct impact on the performance of PV modules. This phenomenon occurs over a period of time with many unpredictable environmental variables indicated above. This situation makes it difficult to calculate or predict the soiling effect on performance. The dust particles vary from one location to the other in terms of particle size, color and chemical composition. These properties influence the extent of performance (current) loss, spectral loss and adhesion of soil particles on the surface of the PV modules. To address this uncontrolled environmental issues, research institutes around the world have started designing indoor artificial soiling stations to deposit soil layers in various controlled environments using reference soil samples and/or soil samples collected from the surface of PV modules installed in the locations of interest. This thesis is part of a twin thesis. The first thesis (this thesis) authored by Shanmukha Mantha is related to the development of soiling stations and the second thesis authored by Darshan Choudhary is associated with the characterization of the soiled samples (glass coupons, one-cell PV coupons and multi-cell PV coupons). This thesis is associated with the development of three types of indoor artificial soiling deposition techniques replicating the outside environmental conditions to achieve required soil density, uniformity and other required properties. The three types of techniques are: gravity deposition method, dew deposition method, and humid deposition method. All the three techniques were applied on glass coupons, single-cell PV laminates containing monocrystalline silicon cells and multi-cell PV laminates containing polycrystalline silicon cells. The density and uniformity for each technique on all targets are determined. In this investigation, both reference soil sample (Arizona road dust, ISO 12103-1) and the soil samples collected from the surface of installed PV modules were used. All the three techniques are compared with each other to determine the best method for uniform deposition at varying thickness levels. The advantages, limitations and improvements made in each technique are discussed.

To,

My mother and father for their unyielding belief, my brother for his love and friends, relatives for their constant support.

ACKNOWLEDGMENTS

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1 INTRODUCTION

1.1 Background

Even though alternative energy technologies are valued with high regard, more than half of the world's electricity generation comes from fossil fuels such as coal, oil natural gas. However, these conventional energy sources are facing number of challenges such as the availability of natural resources but the major challenge is the risk involved with climate change. In order to tackle this issue, countries around the world are supporting the development of alternative energy sources with the recently concluded Paris climate talks emphasizing on this issue. Among all the alternative energy sources available which have the potential to replace fossil fuels, Solar PV emerged as the dominant one in electricity generation. With the governments across the world providing economic incentives for installation of PV modules, production increased and prices reduced leading to an exponential growth of installed PV modules as shown below in figure 1.

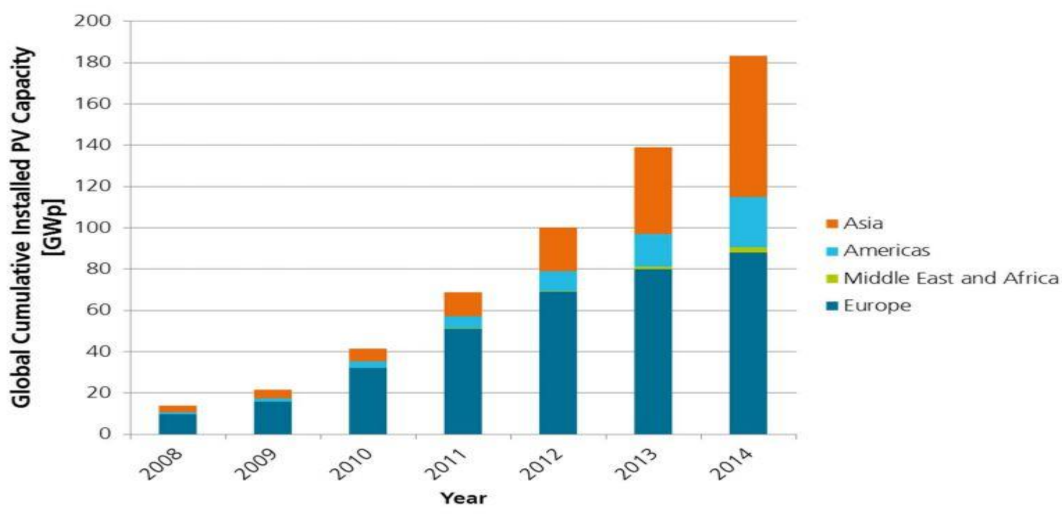

Figure 1 Global Cumulative PV Installation Until 2014

So being the leading source of alternative energy generation there is a need to study the performance of a PV module. Many factors affect the performance of a PV module such as irradiance, climate (ambient conditions), tracking ability, cell efficiency, shading, efficiency of remaining components integral to a PV module. One of these major factors affecting the performance is soiling.

Soiling is the accumulation of dust particles on a PV module as shown in Fig-2. Air pollution particles, pollen, dust, bird droppings and other impurities are some natural sources through which soil is deposited on a PV module. These various factors influencing the soil will vary upon the climatic conditions, geographical locations and orientation of PV module. Soil particles range from 50-2000μm for sand, 2-50μm for slit, and are <2μm for clay, while the atmospheric dust particle sizes typically are in the range of 0.001- 30μm (EPA, USA). One of the main issues with soiling is the depletion of the incident solar radiation. The dust particles on the PV module absorb, scatter and reflect the light which reduces the incident solar radiation. The amount of reduction depends on the dust particle size, density, composition and uniformity of deposition. Soiling came into the picture in late 1970's i.e. the time when there was a surge in concentrated solar photovoltaics because of the energy crisis. CSP is a high irradiance concentrated technology and are well suited to a desert climate. Desert areas are prone to dust and even small dust particles on the CSP lead to very large reflection losses. Sandia National laboratory launched a major project to study the effects of soiling on CSP. Similar studies are being conducted on solar PV to study the effects of soiling on performance. The study by Sayigh et al. in Saudi Arabia found that the reduction of power is 2%, 14% and 30% after 1, 13 and 32 days respectively without cleaning on a PV module at 30° tilt.

According to the study done on PVUSA's south facing 18° tilt rooftop, the annual soiling losses are 6% for a normal year, 7% for a dry year and 4% for a wet year.

Figure 2 Soiled PV Modules.

1.2 Statement of Problem

Previous studies suggest that soiling is a major factor influencing negative performance after irradiance and temperature. However, these studies at various locations, orientations and tilt angles were performed over a certain period of time and are affected by the different climate at different places. The results obtained are location specific and cannot be generalized for every location. So it is imperative to devise an artificial soiling technique which reproduces the natural soiling deposition phenomena and should be repeatable for all the locations. Achieving this accelerated method helps us to deposit pre-characterized soil and ideally the soil on the PV modules from various locations to quantify the soiling losses in a small period of time.

1.3 Objective

There are various previous studies on artificial soil deposition technique but none of them have been standardized yet. The goal for this thesis is to design an artificial soiling chamber to deposit the pre characterized soil and achieve the soil uniformity on a single cell mono crystalline and poly crystalline coupon.

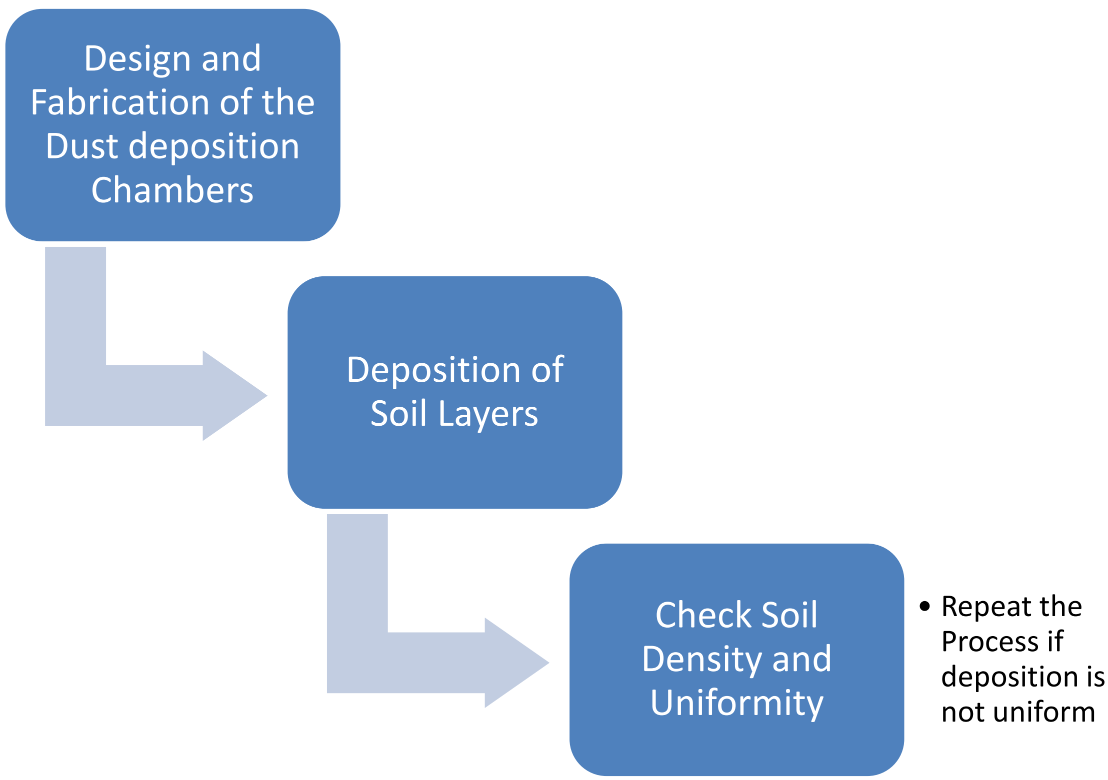

Figure 3 Objective of the Experiment

2 LITERATURE REVIEW

2.1 **Indoor Soiling Method by VidyaShree Rajashekar (ASU-PRL)**

This study presents a working approach to artificially deposit soil onto a single cell laminated PV coupon and perform characterization techniques such as Reflectance and Quantum Efficiency measurements [7]. This section includes a brief description of the design, experimental setup as shown in Fig-4 and characterization measurements performed on the laminated coupon.

The soil used for the study is AZ road dust (ISO 12103-1, A2 fine test dust) which was formulated artificially. The raw material for this pre characterized dust is the dust that settles out of the air around tractors operating in Salt River Valley, Arizona. The dust is caught in a canvas cloth and is dried in an oven, then will be passed through 200 mesh screen (0.0029 in. width opening) and again passed through a 270 mesh screen (0.0021 in.) The soil is mixed with High performance liquid chromatography (HPLC) grade acetonitrile. This solution is then sprayed onto the test module using a High velocity low pressure (HVLP) spray gun with a 1mm nozzle from Central pneumatic. The spray gun has a maximum air pressure of 40 PSI, the cup capacity of 20 fl.oz and air inlet of 1/4"-18 NPS. The knob was adjusted so the spray is along a horizontal direction and the pressure was set to 30 PSI after many trials to deposit a fine layer of soil uniformly. The composition of soil and acetonitrile was set to 15g of AZ road dust for every 1000ml of acetonitrile. This setup was placed inside a cuboidal structure surrounded by an air bag isolating from the outside environment. The spray gun is fixed to the mechanical structure and a laser pointer is attached to the gun to increase the accuracy and achieve consistency in the spray pattern. The soil solution is sprayed onto two mini modules, a monocrystalline silicon cell of area 233 cm^2 and a polycrystalline silicon module of area 144 cm^2. Once the spray patterns are perfected and uniform deposition is achieved, densities (g/m^2) are varied to calculate I_{sc} losses. Reflectance and Quantum efficiency measurements are done and results are discussed.

Figure 4 Experimental Setup [7]

2.2 Evaluation of Soiling Loss with Artificially Deposited Dust-IIT Bombay

Jim J John et al. from IIT Bombay have developed a low-cost artificial dust deposition technique on a module surface in a controlled environment which helped in predicting the soiling losses at various densities [3]. The process is as follows: The soil used for the study is collected from four different climatic regions in India. The test dust was collected from a non-module surface and is filtered by using a wire mesh of 500 μm to filter out any dust particles above this size. Acetonitrile is used as a carrier solvent. Concentration of the solution is maintained at 1.2 gm of test dust for every 100 ml of acetonitrile. Borosilicate, low iron glass (Borosil) of dimension 2 x 2 cm was used as a substrate. Substrate was cleaned using Distilled water, Iso-Propyl alcohol and the dry substrate was weighed. The solution was placed in a spray gun and a magnetic stirrer was used to prevent the dust from settling down in the gun. The substrate was placed at 90^0 angle at a distance of 20 cm from the gun, parallel to the nozzle of the gun. A commercial grade N_2 was attached to the gun. A flow meter of 20 SLM was used to control the flow rate. This setup is placed in a controlled chamber. The pressure is applied and the dust is sprayed at 15 seconds interval until the required density is achieved. The uniformity was measured using an optical microscope and by QE measurements. Using the test dust deposited, the I_{sc} losses varied from 4% to 49% depending on the density of the soil deposition. A uniform dust density of 0.25 mg/cm^2 was achieved. Further tests are performed using soil from different locations. QE measurements are done and results are discussed.

2.3 Influence of Anti-Soiling Coating on Solar Glass of PV modules - Fraunhofer

In order to test the anti-soiling effects on the performance of PV module Elisabeth Klimm et al. have developed two indoor soiling methods [10].

Dry Dust soiling test

The sand type used for the experiment is from Dahab, Egypt. It is of maximum diameter of 1.5 mm which is obtained by sieving. Dry dust is dispensed from a height of 30 cm into the test container. The dust aerosol settles in 3 to 5 min on AS coated substrates. For targeted depositions, the density is determined to be 2.05 g/m^2 with a standard deviation of 0.43 g/m^2. The AS coating is tested by spraying tap water for about 2 min and results are discussed.

Dew soiling test

In this study dew is deposited as a thin water film which is sprayed for 1 sec onto the substrate simulating the morning dew conditions at a distance of 30 cm. After the dew deposition the dry sand is deposited onto the substrate and is dried for 30 min at room temperature. Similarly, the effect of AS coating is studied and results are discussed.

2.4 Artificial Soil Formulation and Application- Sandia Laboratories

In this study, Burton et al. devised a method to deposit NIST-traceable test dust (soot) and particulate matter (AZ test dust) [6]. The following process gives a brief description of the artificial soil deposition using traceable soil components. AZ road test (ISO 12103-1, A2 fine test dust, 0-80micron size) was mixed with a soot mixture composed of 83.3% carbon black (Vulcan XC-723), 8.3% of diesel particulate matter (NIST catalog no. 2975) and 4.2% unused 10W30 motor oil, 4.2% α-pinene in a glass jar and tumbled without milling media in a rubber ball mill drum at 150 rpm for 48 to 72 hr. Variations in grime composition is done by mixing major optical components. Iron oxides Fe_2O_3 (99.98% trace metal basis) and in-house synthesized gothite (FeO (OH)) were mixed as primary spectral components. Blended soil types are formulated with 40 wt. % iron oxide pigment and 60 wt. % AZ road dust/soot. Aerosolizable suspensions were prepared by mixing 3.3 g of the dry blend with 275 ml of acetonitrile as a carrier solvent

Schott borofloat was used as a test substrate after cleaning with a commercial degreaser and rinsing in distilled water followed by ethanol. The dry coupon was weighed with a Mettler Toledo XP205 balance with 0.00001 g resolution and is placed at 45° angle inside a filtered spray chamber. Coupons were prepared by spraying the soil suspension in 25 mL aliquots with a HVLP (high velocity low pressure) automotive detaining gun (Transtar gravity fed model 6618, 1.0 mm nozzle) held approximately 30 cm from the coupon surface. The detaining gun was aimed a few centimeters past the right edge of the coupon and slowly moved to the left until the spray solution was on the entire coupon. The procedure is continued until the density requirements are met. A poly-crystalline silicon wafer was used to measure the transmittance and get the spectral response. The spectral response of each sub coupon was evaluated by UV/VIS spectroscopy from 300 to 2500 nm. Quantum efficiency measurements were performed and the results are discussed.

3 METHODOLOGY

3.1 Soil Type and Background

3.1.1 Arizona Road Dust (ISO 12103-1 A2 Fine Test Dust)

Arizona sand has been used traditionally for testing filtration, automotive and heavy equipment. Variety of names has been used for Arizona sand such as Arizona road dust, Arizona silica, AC fine and coarse test dusts. Many industrial specifications require the use of Arizona test dust and refer to the various names mentioned above for different industries. Usage of Arizona test dust as a testing soil dates back to 1940. But for large periods there was no standard on the dust manufacturing as there are lot of factors involved such as particle shape, size and analysis methods. After much needed study done on this issue an acceptable method of manufacture was prepared to get fine test dust from Arizona sand. The process is as follows: First the raw dust is dried in an oven. Then the resulting dry dust is sifted through a 200 mesh screen (0.0029 in. width of openings) to isolate the hard particles out. The relatively finer sand is then sifted through a 270 mesh screen (0.0021 in. of width opening) to get more fine dust.

This fine dust is divided into four different grades- ISO 12103-1 A1 ultra-fine test dust of 0-10micron size, ISO 12103-1 A2 fine test dust of 0-80-micron size, ISO 12103-1 A3 medium fine test dust of 0-80-micron size but with a lower 0-5-micron content than that of A2 dust and ISO 12103-1 A4 coarse test dust of 0-180 micron size. The standardized or particulate matter we use for all the experiments in this study is the Arizona road dust (ISO 12103-1 A2 fine test dust).

3.1.2 Collected Soil at ASU-PRL, Mesa

This soil is collected from the surface of PV modules present at ASU-PRL. This is done by scraping the dust off with a squeegee and a brush onto a Zip lock bag. The soil weight is then measured by a high resolution weighing scale Mettler Toledo (AG285, resolution 0.001 gm).

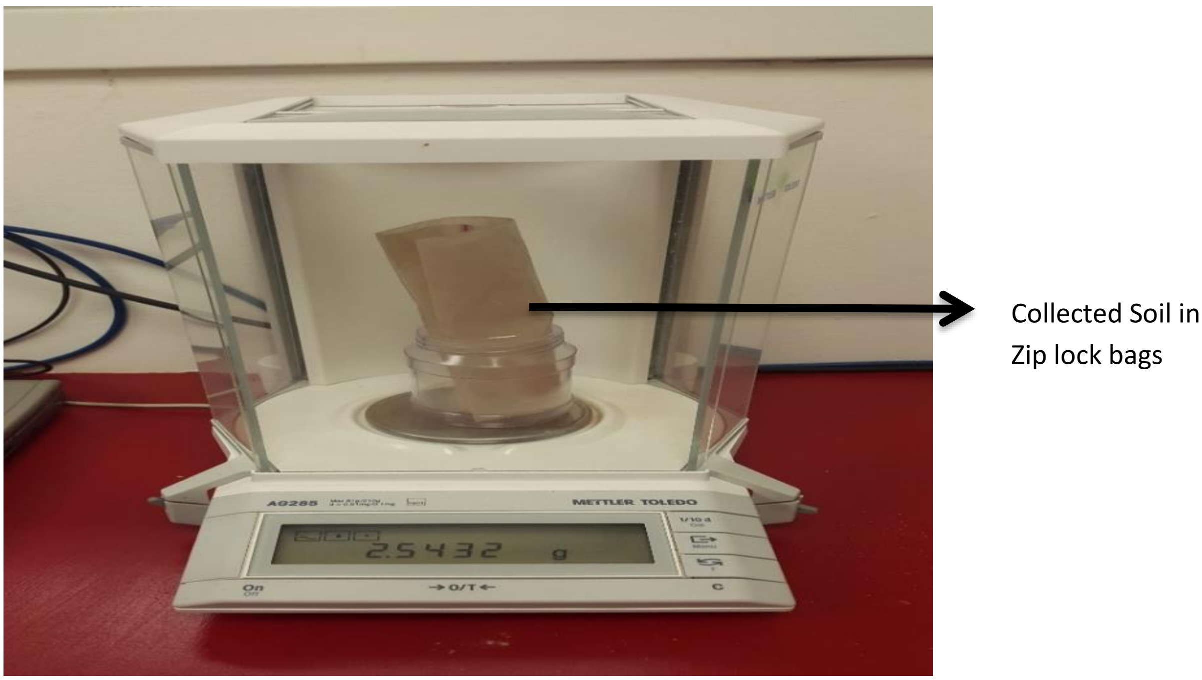

Figure 5 Collected soil weighing measurement

Figure 6 Collected soil (left) and AZ dust (right) samples

3.2 Test Modules

Monocrystalline and Polycrystalline silicon module without Anti reflection coating were used for this study.

3.2.1 Construction of Mono and Polycrystalline Silicon Modules

The constructions of both the silicon module types are identical. The front cover is made of Soda lime glass which is a tempered, low iron content glass with high transmittance properties. This is followed by a commonly used encapsulant Ethylene Vinyl Acetate (EVA) which acts as an adhesive between glass and cell with cerium oxide particles (a UV stabilizer). This is followed by Silicon cell (multiple cells for poly crystalline) followed by another layer of EVA. A tedlar back sheet was used as the rear layer made of Polyvinyl Fluoride.

[Table-1] Layers of Crystalline Silicon Technology Test Modules

Boro Silicate Glass
Ethylene Vinyl Acetate (EVA)
Silicon Cell/Cells
Ethylene Vinyl Acetate (EVA)
Tedlar Back sheet

The polycrystalline silicon module has 18 cells which are connected in series. Monocrystalline silicon module is a single cell laminated coupon.

[Table-2] Specifications of the Test Modules [7]

Variables	**Mono-Silicon**	**Poly-Silicon**
Number of Cells	1 cell	18 cells in series
Cell Dimension	15.4 cm by 15.4 cm	5.7 cm by 1 cm
Total Cell area	233 cm^2	144 cm^2
I_{sc}	9.33 A	0.18 A
V_{oc}	0.59 V	10.71 V
P_{max}	3.5 W	1.48 W

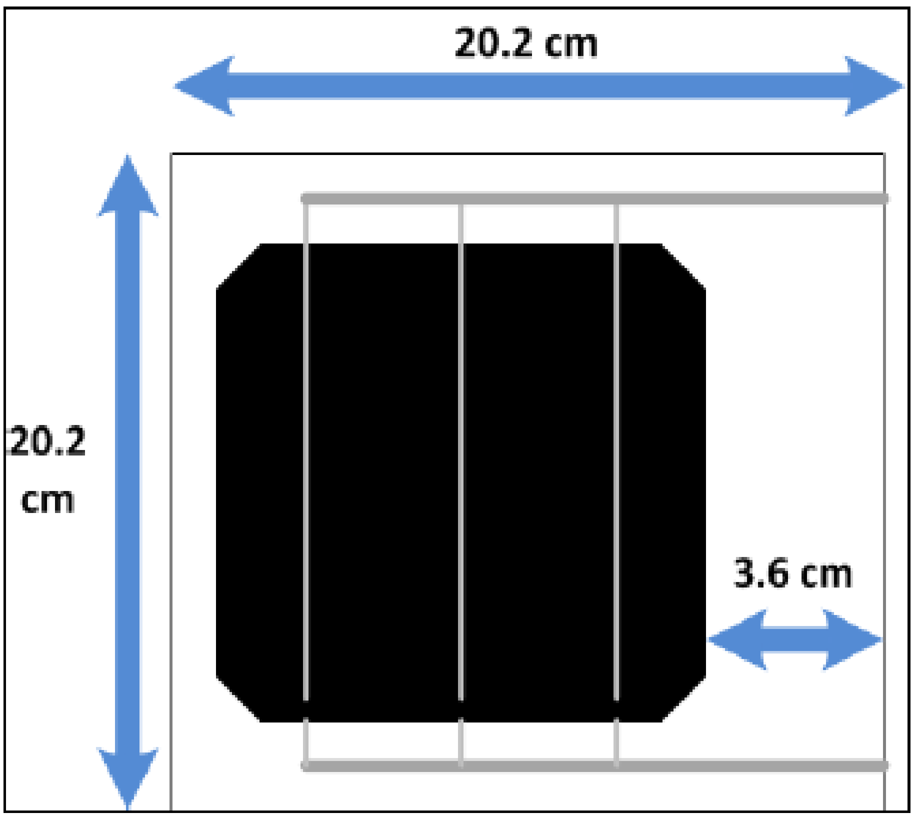

Figure 7 Monocrystalline Silicon [7]

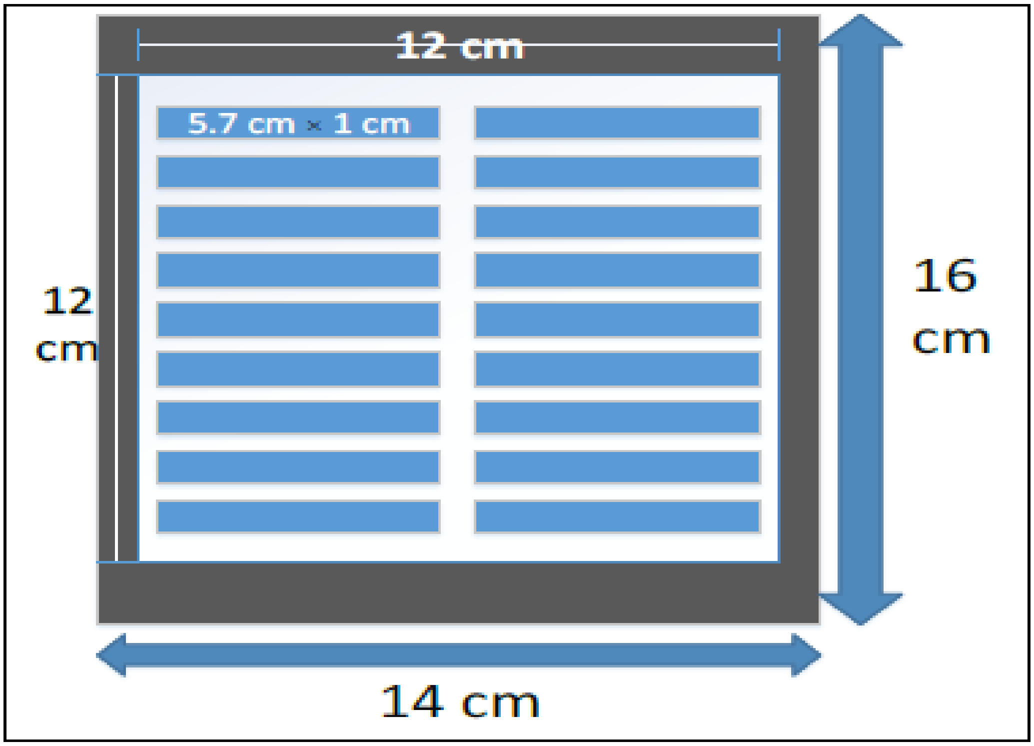

Figure 8 Polycrystalline Silicon [7]

3.3 Soil Density Measurement

Commercially available microscopic slides of the area 2.5 × 7.6 cm were used to determine the soil density. The slides are placed on the test module and the density measurements are done by calculating the difference in weight of the slides before and after soiling divided by the area of the microscopic slides. The measurements are carried out by using Mettler Toledo (AG285, resolution 0.001 gm). The density is measured in g/m^2.

3.4 Soil Uniformity Measurements

3.4.1 Microscopic Slide Method

As discussed in the previous section, the slides are placed on four sides of the test module and the density measurements are calculated by measuring the difference in weights of all the four glass slides before and after soiling. The standard deviation of the difference in densities on all four sides determines the soil uniformity across the test module.

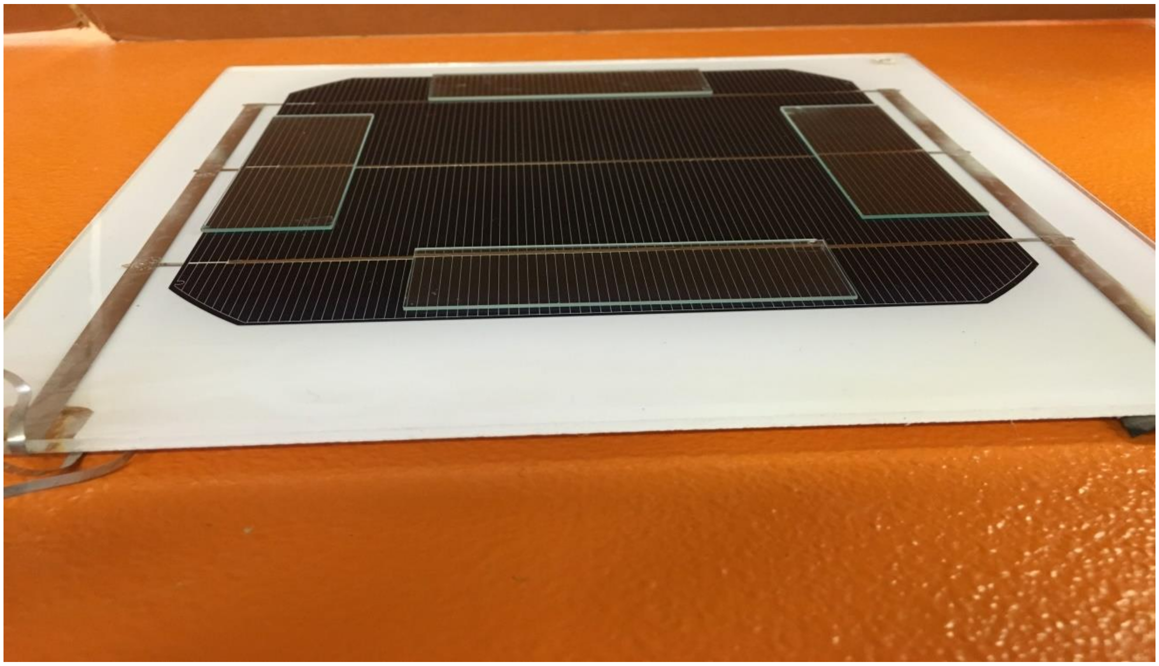

Figure 9 Microscpic Slide Sample Location

3.4.2 Isc Measurement Using Solar Simulator

The solar simulator works on the principle of sending a beam of xenon light in the spectrum range ideal for replicating the solar beam irradiance. The Isc values of the test module are measured before and after soiling. For the single cell monocrystalline silicon, the Isc values are taken for multiple soiling cycles and correlate them to check the consistency of the values and hence the uniformity. For polycrystalline module, Isc values of each individual cell are calculated and the %Isc difference of the non-soiled and soiled cells are plotted to determine the uniformity.

Figure 10 Indoor Solar Simulator

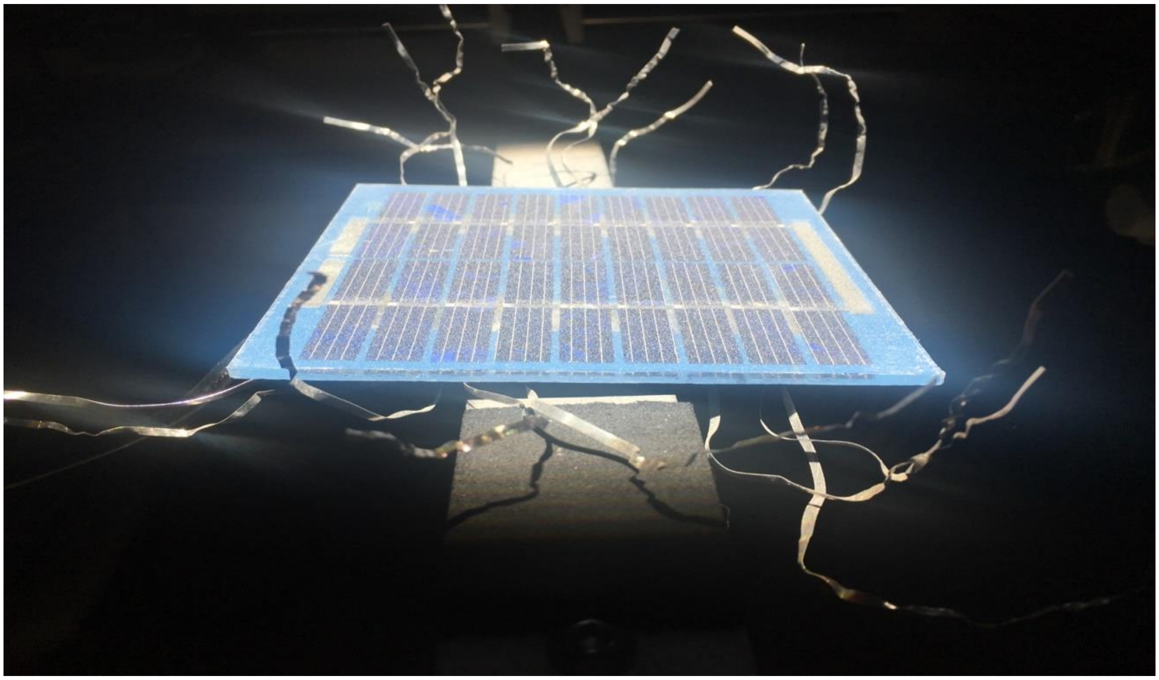

Figure 11 Test Module in Solar Simulator

3.5 Design Components

3.5.1 Gravity Deposition Method

Plexi Glass Sheet: Plexi Glass sheets are made of Acrylic (polyacrylate) material. In this design Plexi glass was used to build an environment control chamber for uninterrupted soil deposition.

Figure 12 Plexi Glass Sheets

Mechanical Structure: A mechanical structure is built using aluminum rods to place the Plexi glass sheets around the structure.

Soil Dispensing System: The soil dispensing system was designed in Solid Works software to the required dimensions and is then 3D printed to get the accurate design. 3D printing is done at ASU on a LulzBot TAZ 5 printer. It is a versatile, high performance printer mainly used for industrial purposes. Polylactic acid, generally referred as PLA is the material used for 3D printing the soil dispensing system. The material is heated to

205^0C to convert it to molten state and then the design is printed which solidifies to give us the 3D printed soil dispensing system.

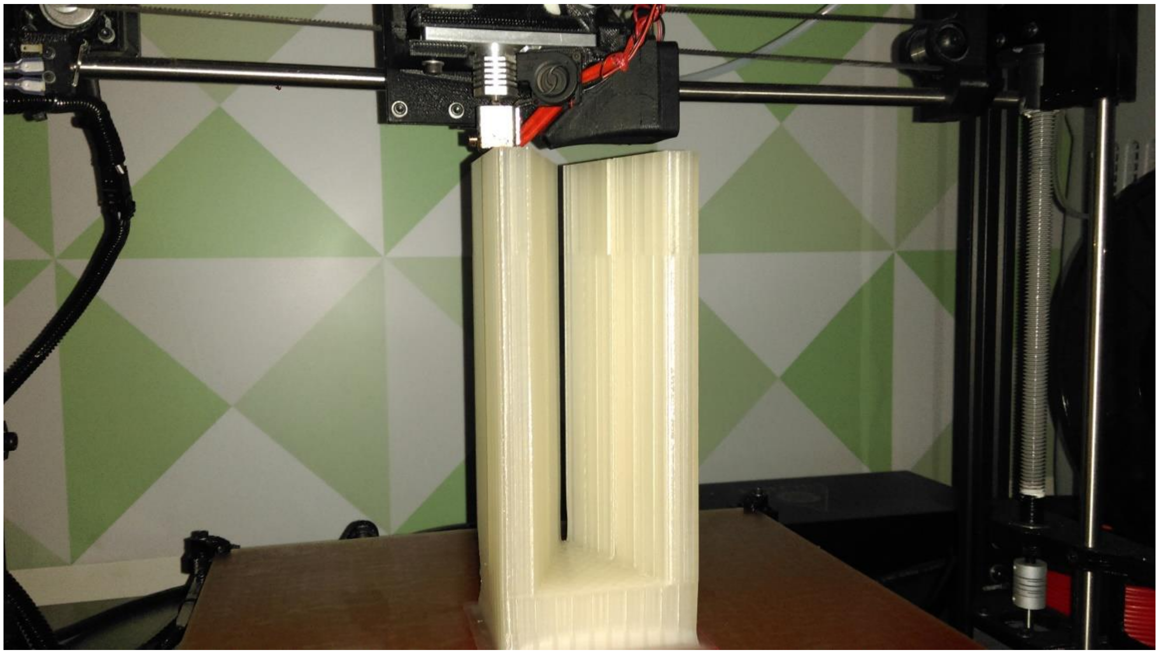

Figure 13 Soil Dispensing System 3D Printed Component

Vibration System: Two mini vibration systems are used to instill vibrations for eliminating clumps in sand and allowing the sand to fall freely with the help of gravity.

3.5.2 Dew Deposition Method

Nitrogen Gas: A small burst of air is needed to create a dust cloud but the normal compressed air contains pollutants such as carbon which might affect the dust composition. To avoid this gaseous nitrogen burst is used to create a dust cloud.

Dust Vial: A dust vial is a small container with one open end at the top used to hold the dust before spraying it with the nitrogen gas.

3.5.3 Humid Deposition Method

Humidifier: A humidifier is used to produce humidity acting as a small HVAC system for the chamber. Humidity meter is used to monitor and maintain the humidity in the chamber.

3.6 Gravity Deposition Method

As we are aware by now devising an artificial soiling technique helps us to evaluate the soiling losses on a PV module in a short period of time and estimate the cleaning cycles required for a plant. In this method we have devised a gravity assisted soil dispensing system to directly deposit the sand onto to a mini-module. The following process gives a description of the deposition mechanism.

3.6.1 Setup

First we have built a mechanical cuboidal structure made of aluminum rods. The structure is then enclosed with plexi glass sheet to build a chamber to achieve a controlled environment. The soil dispensing system is modelled in solid works to the required dimensions and is 3D printed. The material used for 3D printing is Polylactic acid (PLA). The 3D printing is done by melting the PLA material at 205°C to convert it to molten state and is printed according to the 3D model done in solid works. The 3D printed soil dispenser acts like a container to hold the dust and the slit at the bottom acts as a funnel to dispense the soil onto the mini module. This dispensing system is fixed to a slider to get to and fro movement necessary for depositing the dust across the mini module. The motion was provided manually initially and was later automated by a DC motor attached to a timing belt which was attached to pulleys on both ends. A mesh screen is placed in between the soil dispenser and the mini module at the bottom of the chamber to filter out the hard particles and achieve uniform deposition. Two mini vibration systems were attached to the soil dispensing system to instill vibrations to the soil which helps us reduce the clumps formed in the dust because of the moisture.

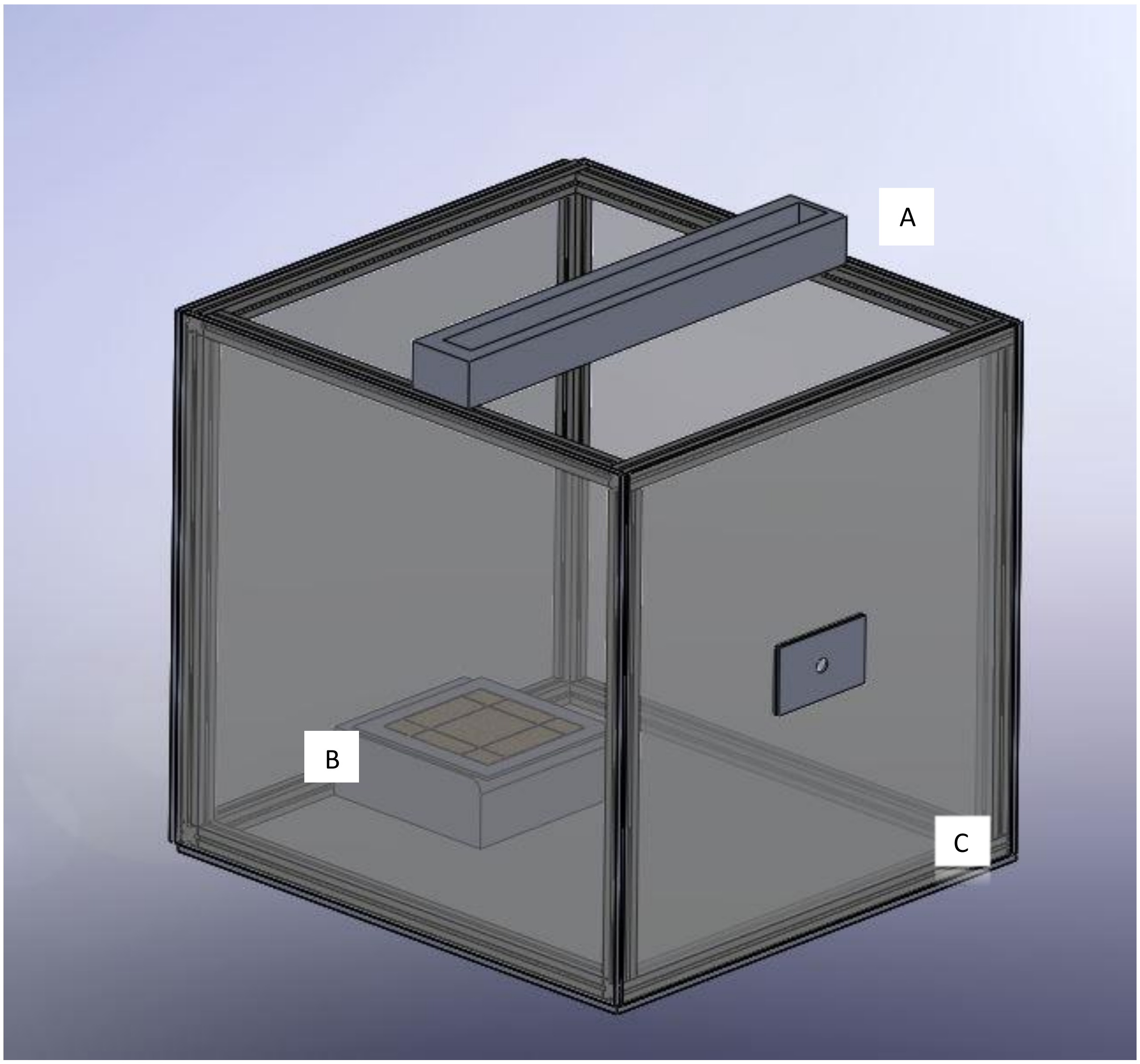

Figure 14 Artificial Chamber and Components 3D Design

A-Soil dispensing system, B-Sample soiled test module, C-Artificial chamber

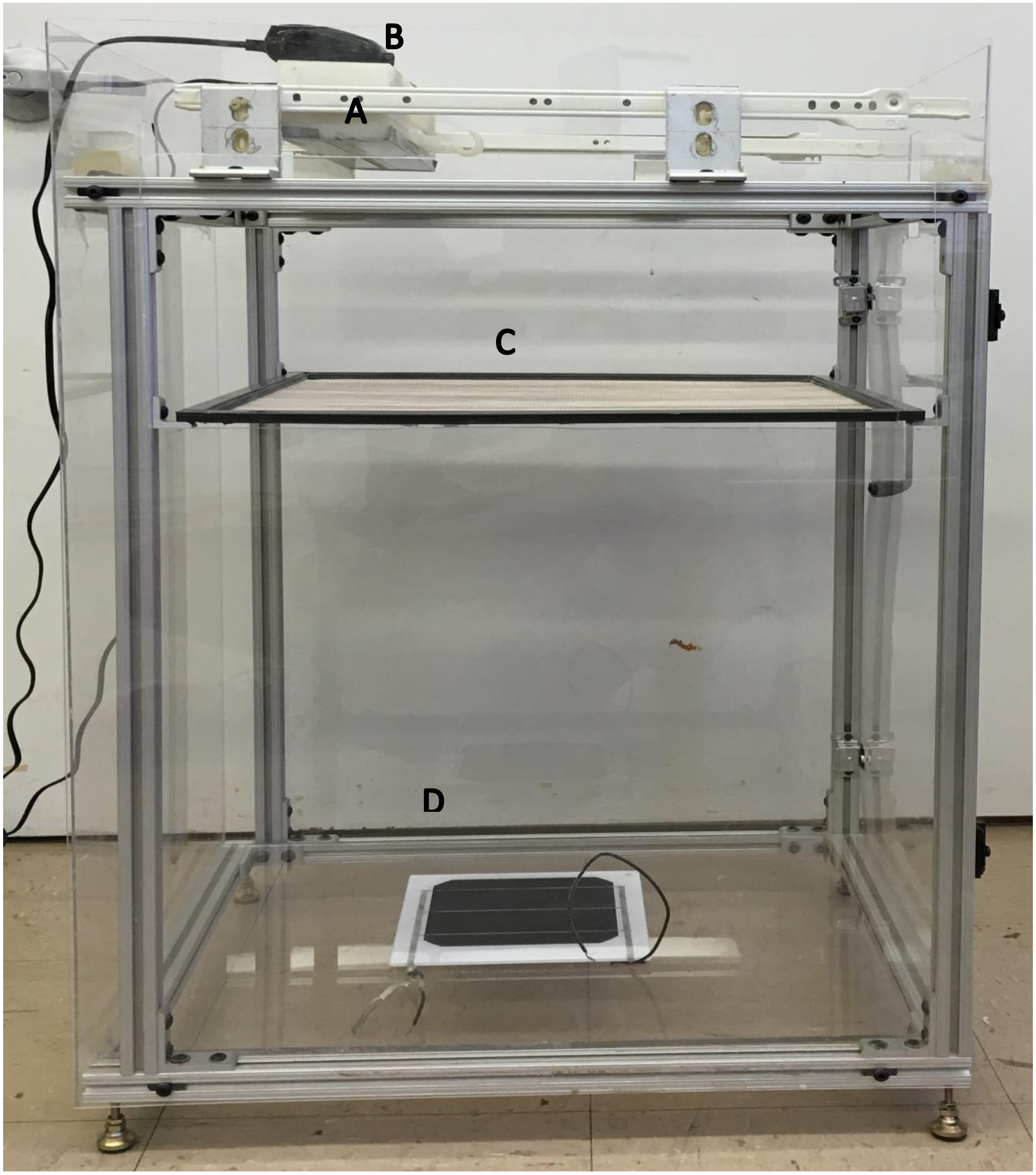

Figure 15 Artificial Chamber and Components Side View

A-Soil dispenser, B-Vibration systems, C- Mesh screen, D- Sample mini module

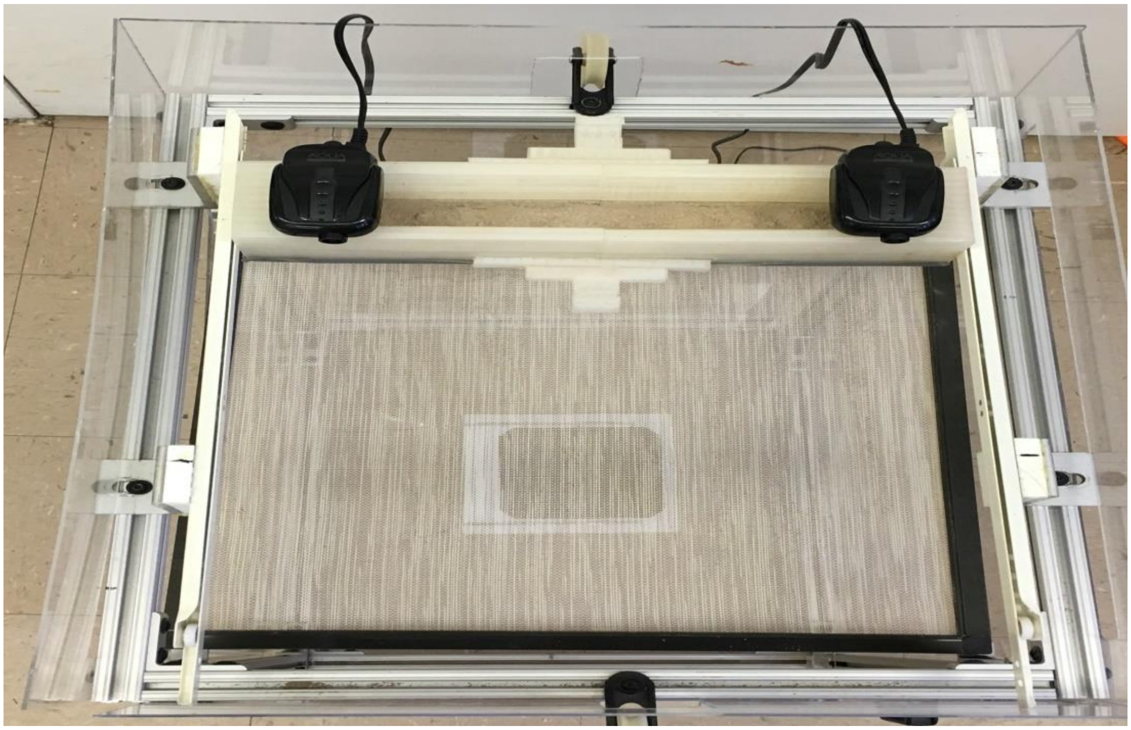

Figure 16 Artificial Chamber and Components Top View

3.6.2 Working

After the setup is done, the mini module is placed in a freezer for an hour to form a thin film of water which is similar to the dew deposited on the modules in the environment. The sample is then taken out of the freezer and placed in a stand horizontally on the bottom of the chamber. The vibration system is then turned on and the slider is moved horizontally to and fro. The sand then starts dispensing from the soil dispenser with assist from gravity onto the mini module. The sample is then baked in an oven at 65°C for 1 hour to make the dust stick to the module. Soil uniformity of the module is checked using microscopic slides which are placed on four sides of the module and calculating the difference in weights of the soiled and non-soiled slides.

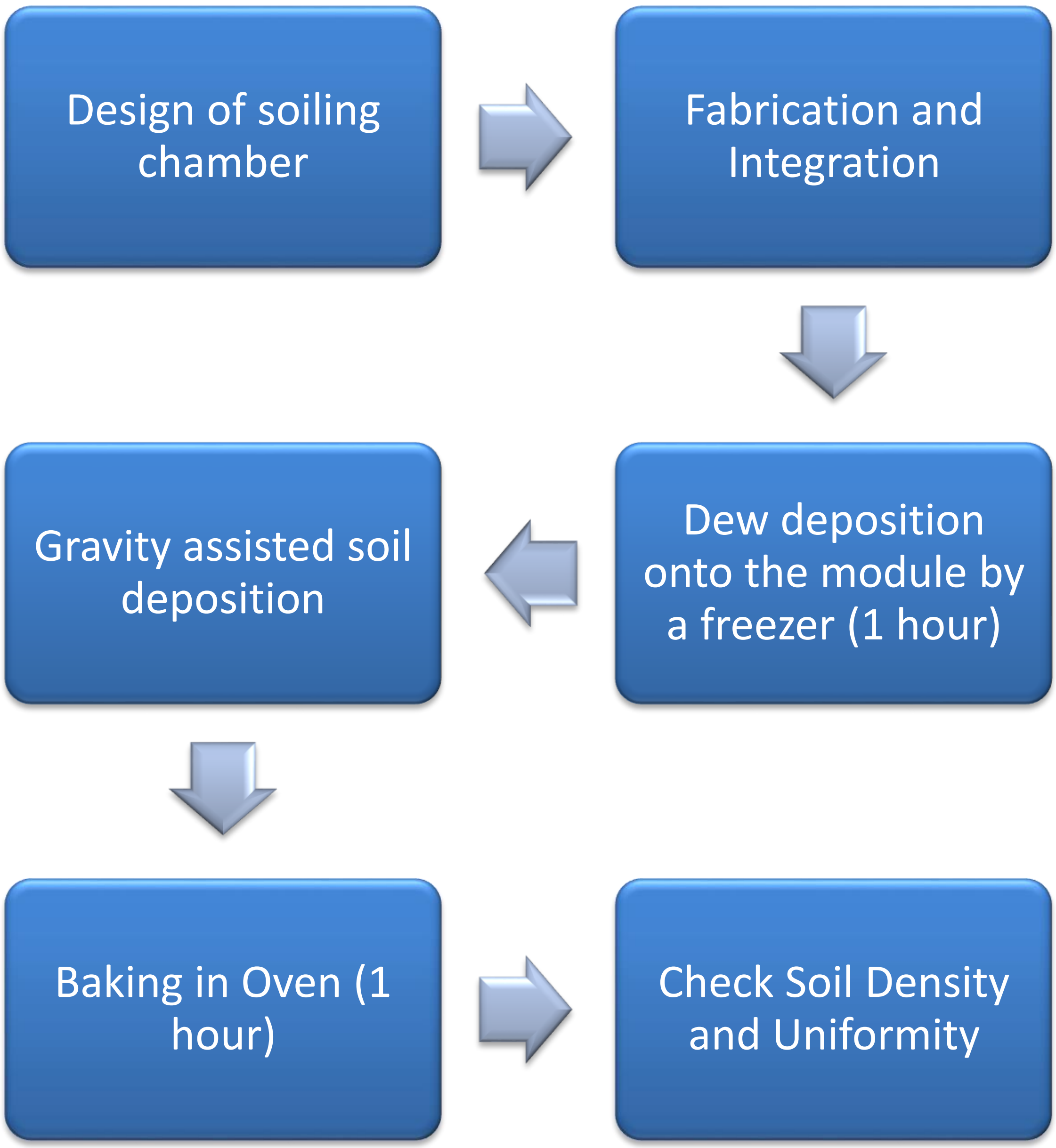

Figure 17 Gravity Deposition Method Flow Chart

3.7 Dew Deposition Method

Because of the difficulties found in gravity based deposition, to build a near ideal model for artificial dust deposition we have developed another technique called the dew deposition technique.

3.7.1 Setup

The main concept behind this method is to create a dust cloud using compressed gas which then deposits onto the module. For this method we used the same mechanical structure with plexi glass after dismantling the soil deposition component from the gravity method along with the mesh screen as the chamber with a controlled environment. This chamber contains a small dust dispensing vial at the bottom. The compressed gas used for this study is Nitrogen.

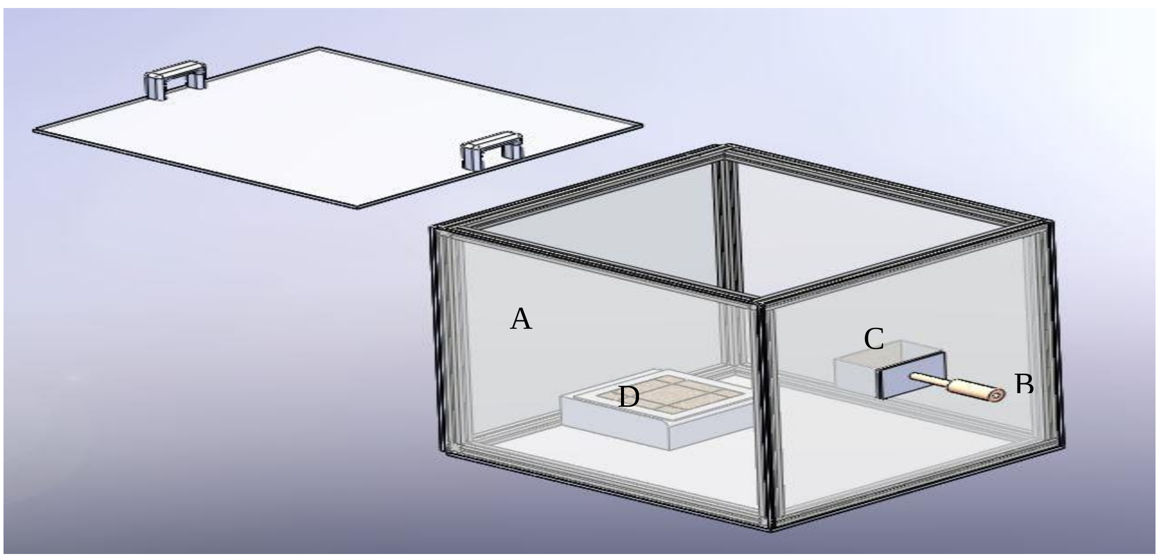

Figure 18 Dew Deposition Method 3D Design

A-Soiling Chamber, B- Compressed gas nozzle, C- Dust Vial, D- Sample test module

3.7.2 Working

The test sample is kept in a freezer for an hour. After the deposition of thin film of water spread evenly across the module, it is placed in the chamber on a stand. The stand can be adjusted to required tilt angles. As mentioned above, the soil used in this method is Arizona Road dust (ISO 12103-1 A2 fine test dust). Measured dust of about 2 grams is placed in the dust vial at the bottom of the chamber. A burst of Nitrogen gas onto the measured dust in the dust vial creates a dust vortex of swirling gas carrying the dust particles inside the enclosed chamber and gets deposited onto the module with the effect of gravity. The test sample from the freezer is kept in the vortex for about a minute. The dust particles settle on to the water film on the module which prevents it from sliding off. The module is then taken out and kept in an oven for 1 hour at 65°C for baking. The dust gets stuck to the test sample. The soiled sample is then taken out and uniformity measurements are performed.

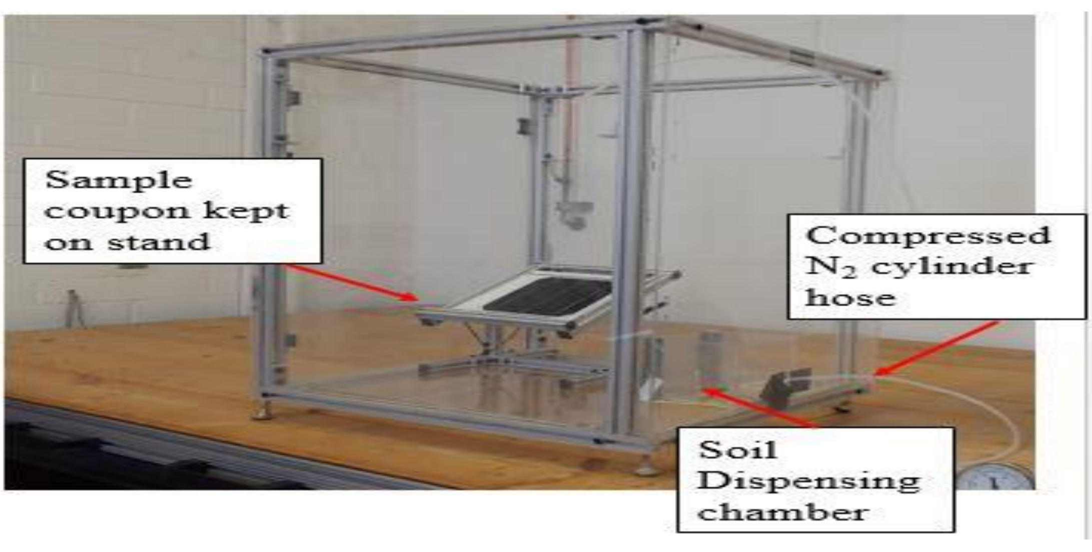

Figure 19 Dew Deposition Artificial Chamber and Components

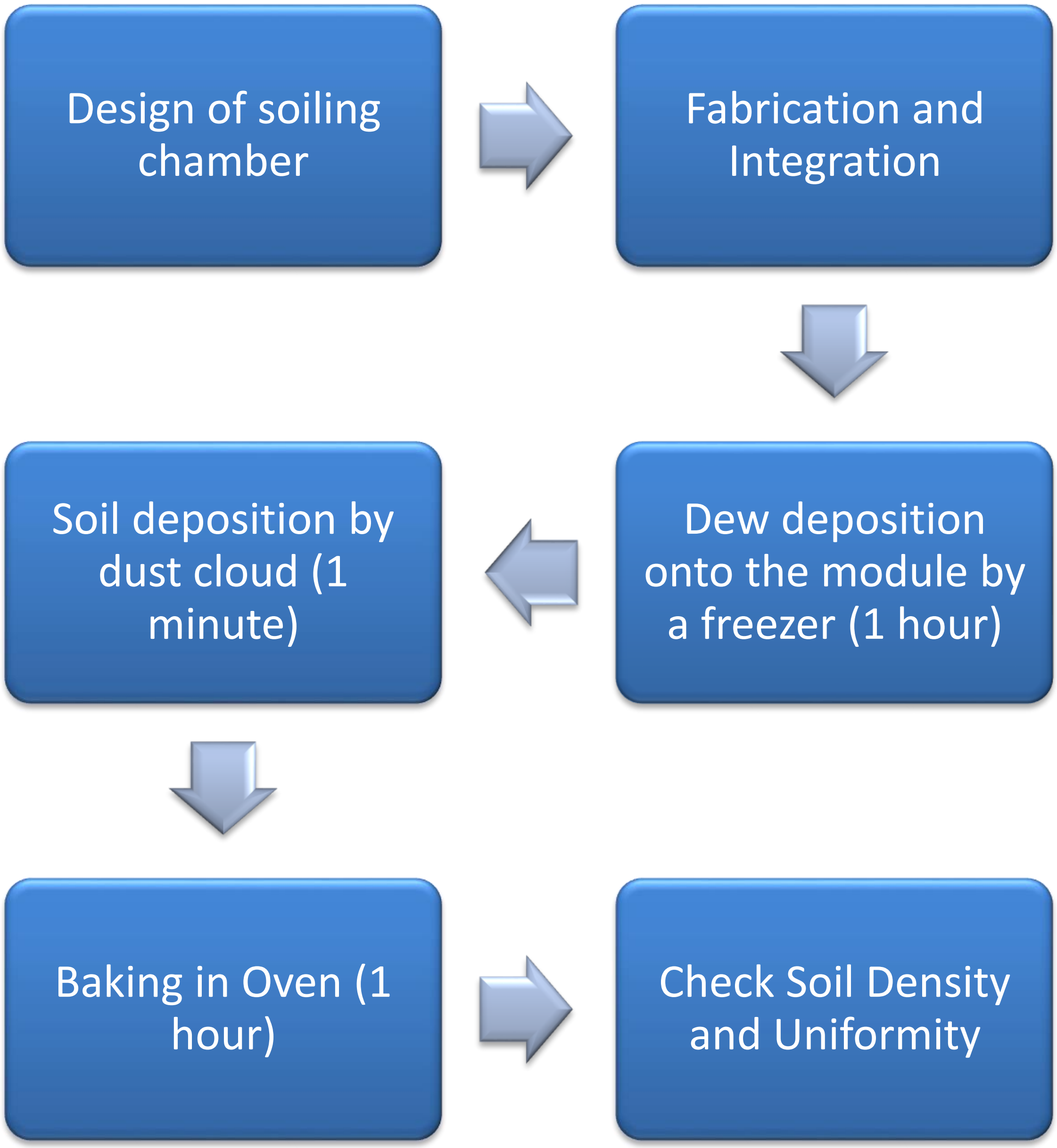

Figure 20 Dew Deposition Method Flow Chart

3.8 Humid Deposition Method

The third technique of dust deposition is similar to the dust deposition with freezer method. A humidifier is the new component in this technique which eliminates the freezer technique.

3.8.1 Setup

For this method we used the same mechanical structure with plexi glass after dismantling the soil deposition component from the gravity method along with the mesh screen as the chamber with a controlled environment. This chamber contains a small dust dispensing vial at the bottom. The compressed gas used for this study is Nitrogen. Another component added for this method is a humidifier.

3.8.2 Working

The module is placed in the chamber on a stand. The stand can be adjusted to required tilt angles. A humidifier is used to create a mist cloud over a module to deposit a thin film of water. After 15 minutes, measured dust of about 2 grams is placed in the dust vial at the bottom of the chamber. A burst of Nitrogen gas onto the measured dust in the dust vial creates a dust vortex of swirling gas carrying the dust particles inside the enclosed chamber and gets mixed with the humidified air. The effect of gravity helps the humidified air and dust mixture to settle on the module. The module is left inside the chamber for a minute. The module is then taken out and kept in an oven for 1 hour at 65°C for baking. The dust gets stuck to the module. The soiled sample is then taken out and density, uniformity measurements are done.

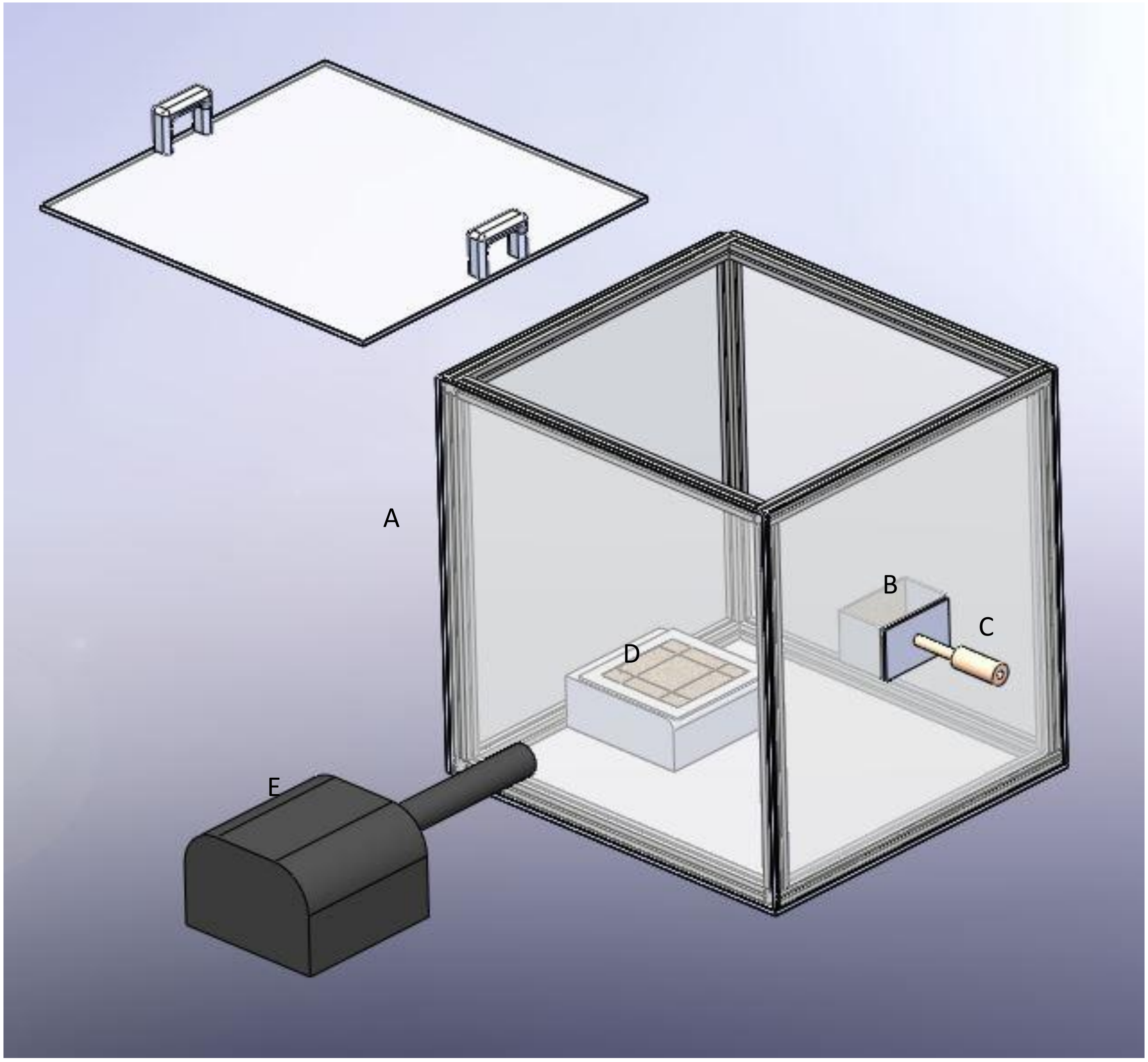

Figure 21 Humid Deposition Artificial Chamber and Components 3D Design

A-Soiling Chamber, B- Compressed gas nozzle, C- Dust Vial, D- Sample test module, E- Humidifier

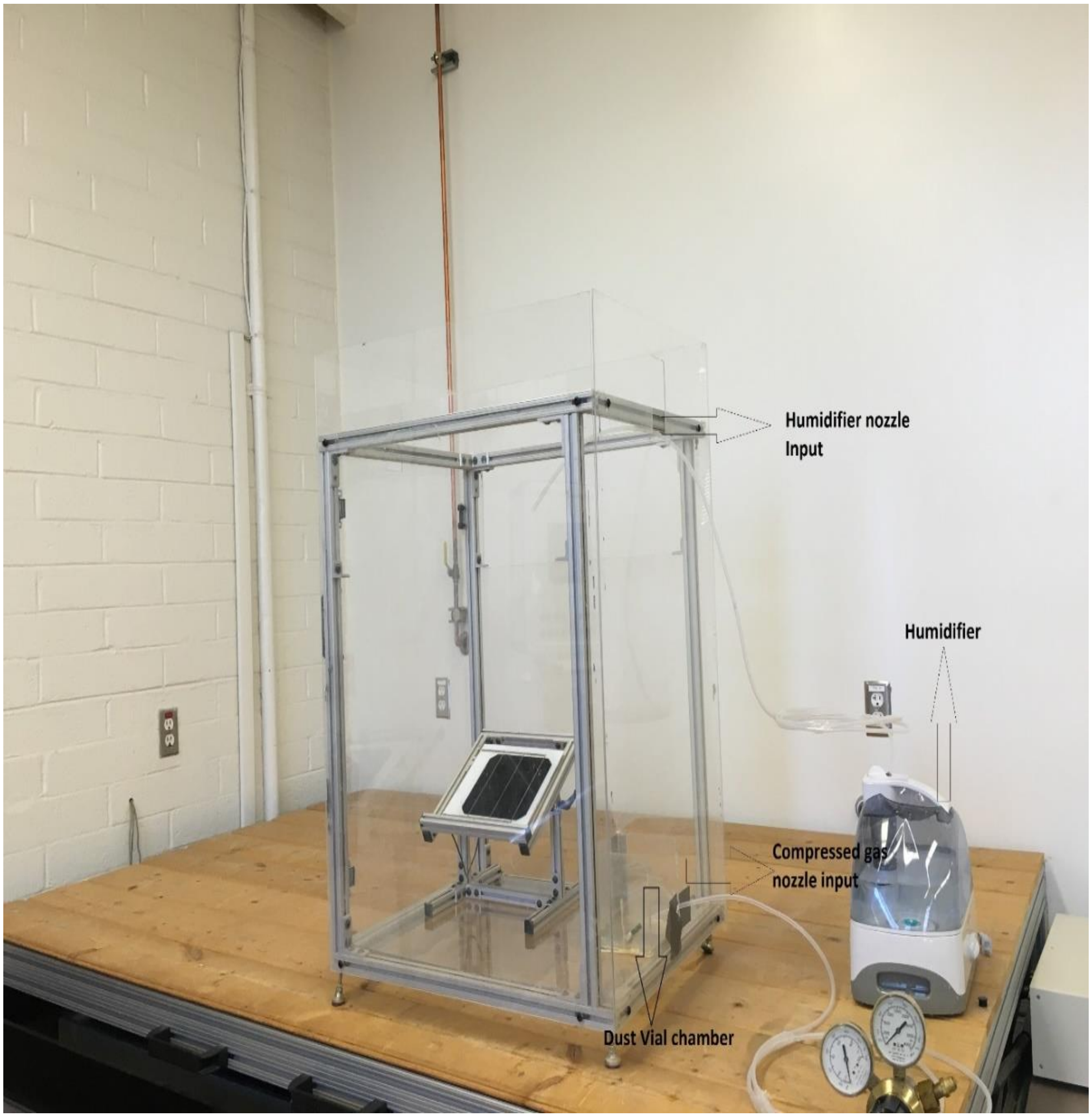

Figure 22 Humid Deposition Artificial Chamber and Components

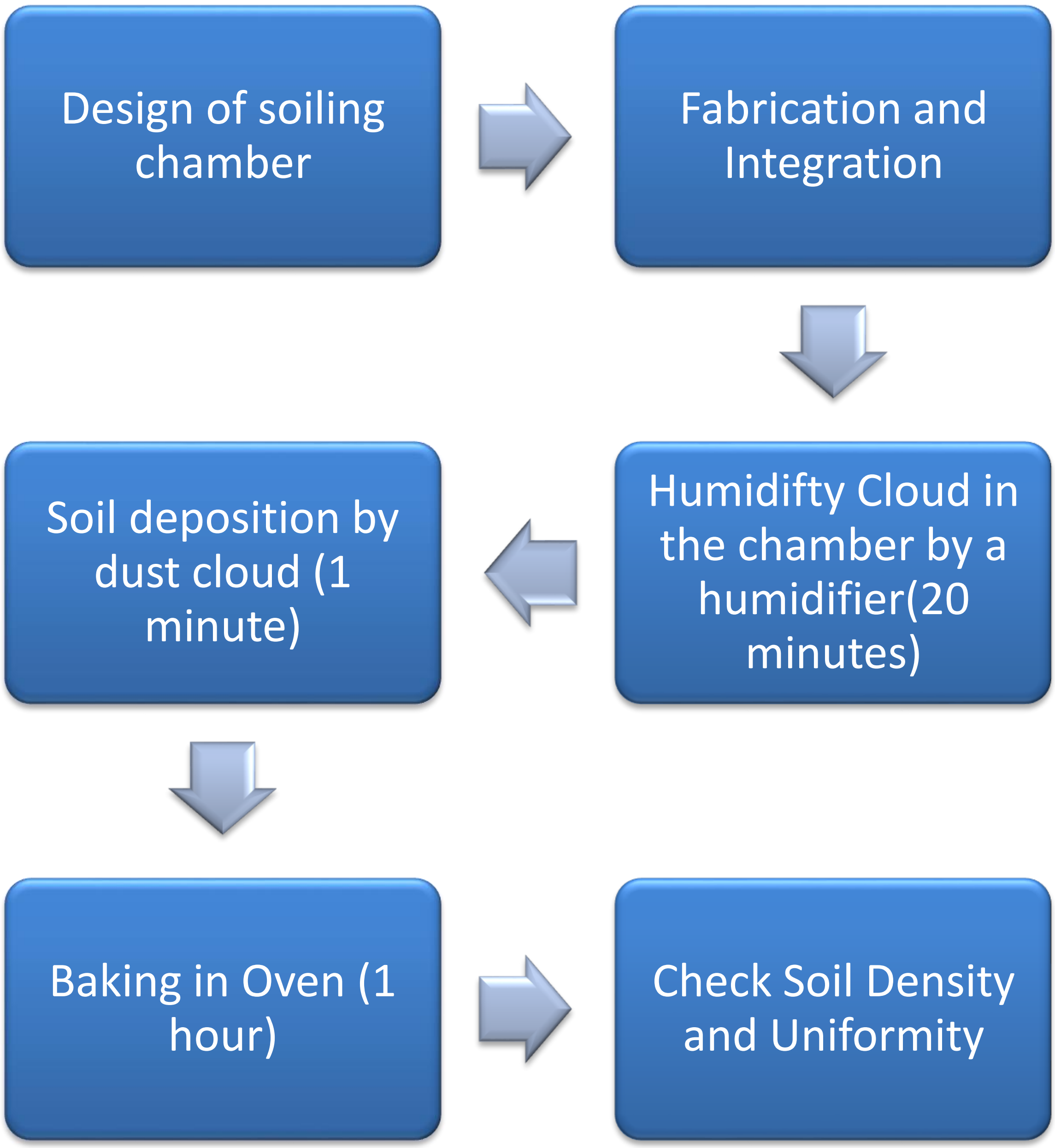

Figure 23 Humid Deposition Method Flow Chart

3.9 Soil Deposition on Glass Coupons by Dew Deposition Method

For the dust deposition on these Glass coupons, dew dust deposition technique is used. There are three Glass samples on which the dust needs to be deposited. On one glass sample AZ road dust was for 5 cycles was deposited, for the second and third sample collected soil for 10 and 15 cycles respectively was deposited. The technique used for this deposition is the dew dust deposition. However, the baking time was increased from 1 hour to 4 hours for the same temperature as discussed previously at 65^0C. The weight of the bare glass and the soiled glass at each cycle was measured to calculate the soil density value for each cycle and the overall density for each glass sample.

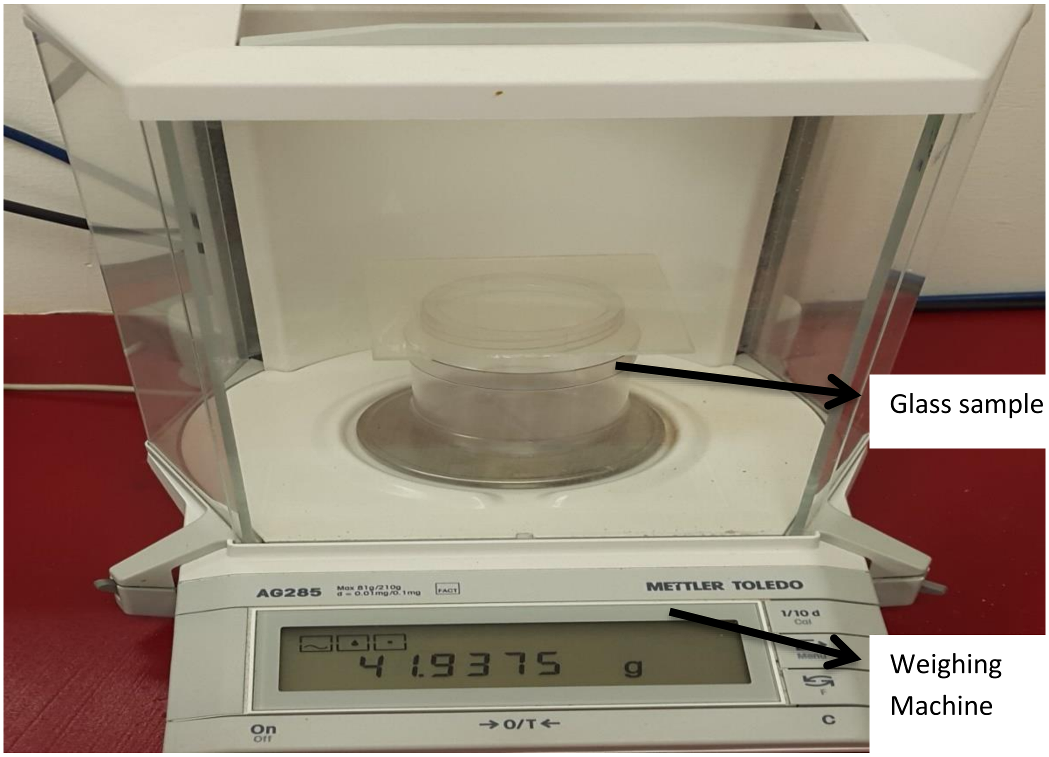

Figure 24 Weighing Scale with Glass Coupon

Also, the transmittance of the glass is measured by using the indoor solar simulator. First a reference cell is placed on the solar simulator equipment and focusing the xenon light from the simulator onto the reference cell and by using a Fluke multi meter the current in the form of voltage (mv) of the cell is calculated. Then the bare glass is placed on the reference cell and the voltage value is calculated. Similarly, the soiled glass voltage is calculated for each cycle. This is done to measure the % voltage loss after the soiling cycles are completed and determining if the losses are consistent and the technique is repeatable.

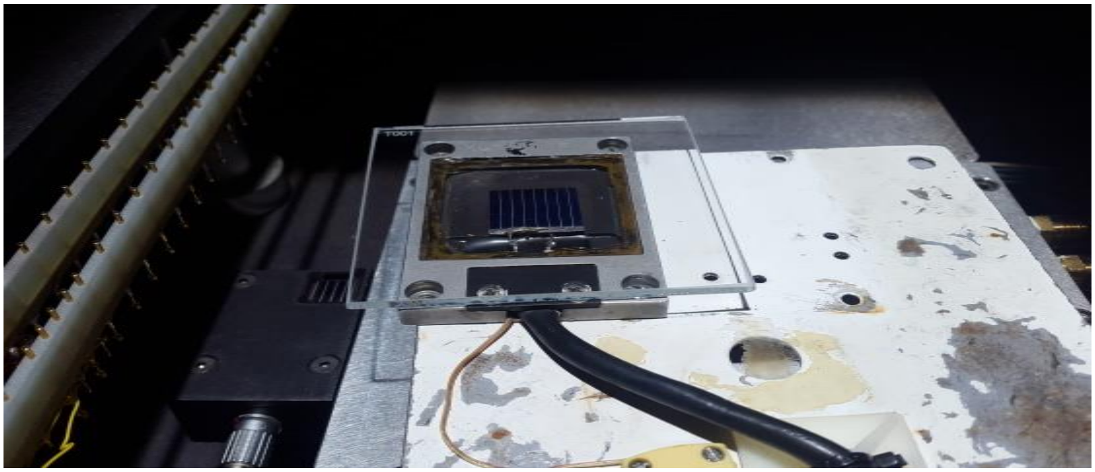

Figure 25 Reference Cell with Bare Glass

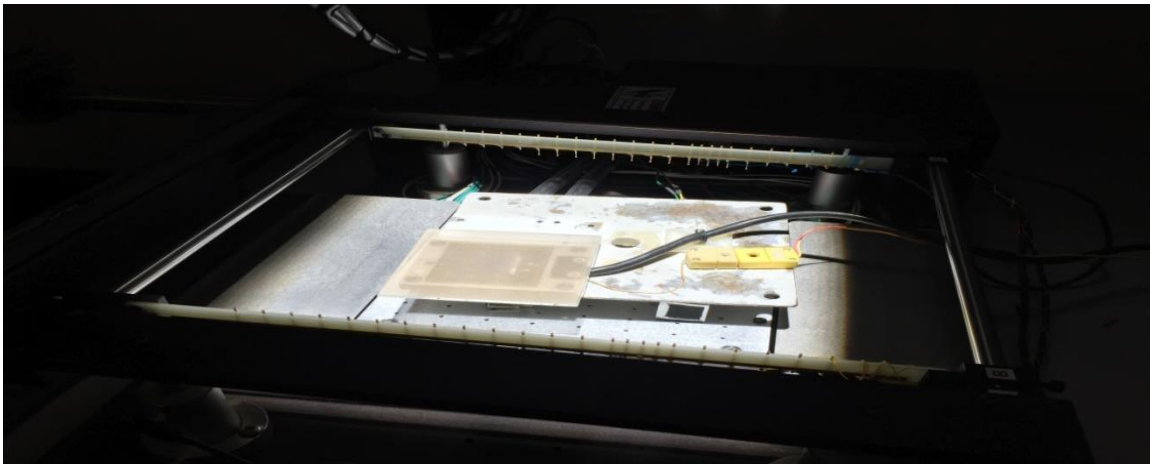

Figure 26 Reference Cell with Soiled Glass in a Solar Simulator

4 RESULTS AND DISCUSSIONS

To get accurate data and repeatable results, the sample test module of both the monocrystalline and polycrystalline module remains constant. The microscopic slides used for density and uniformity measurements remain the same throughout the experiment.

4.1 Soil Density and Uniformity Measurements for Monocrystalline Silicon

4.1.1 Gravity Method

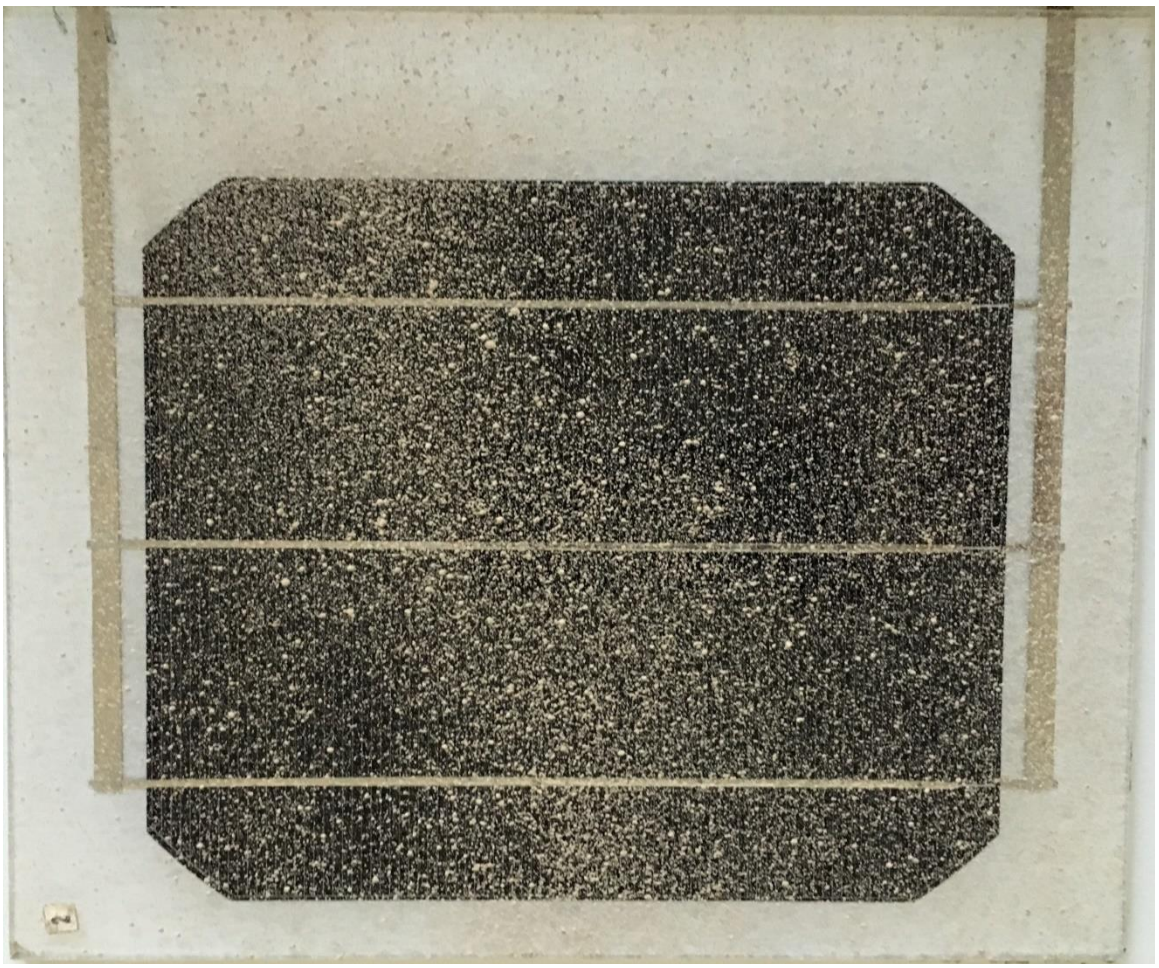

Figure 27 Gravity Method Soiled Test Module-Visual Examination

From the above picture it is clear to the naked eye that the soil deposition is not uniform. The non-uniformity can be better depicted by plotting a graph of the difference in microscopic slides weight before and after soiling.

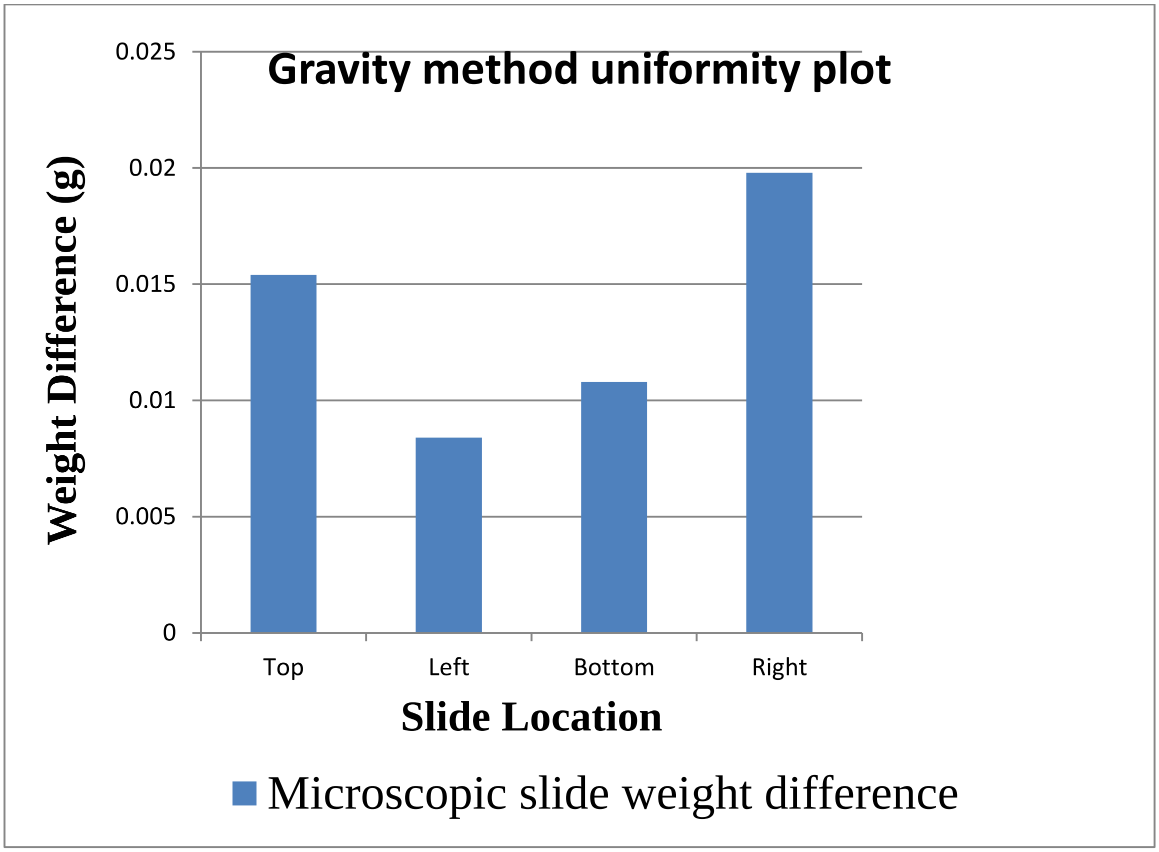

Figure 28 Gravity Method Uniformity Bar Plot-AZ Dust-1 Cycle

Fig-29 shows the considerable weight difference between each slide which is a clear indicator of the soiling non-uniformity. The standard deviation is found out to be 0.44%. The density value had varied from 4.4 to 8.1 g/m^2. This non-uniformity could be attributed to the moisture in the AZ dust which caused the formation of clumps. Vibration systems were used to remove the clumps but the irregularities in the vibrations did not remove the clumps completely. A mesh screen was also used to remove large dust particles but it couldn't filter out all the large particles.

4.1.2 Dew Method

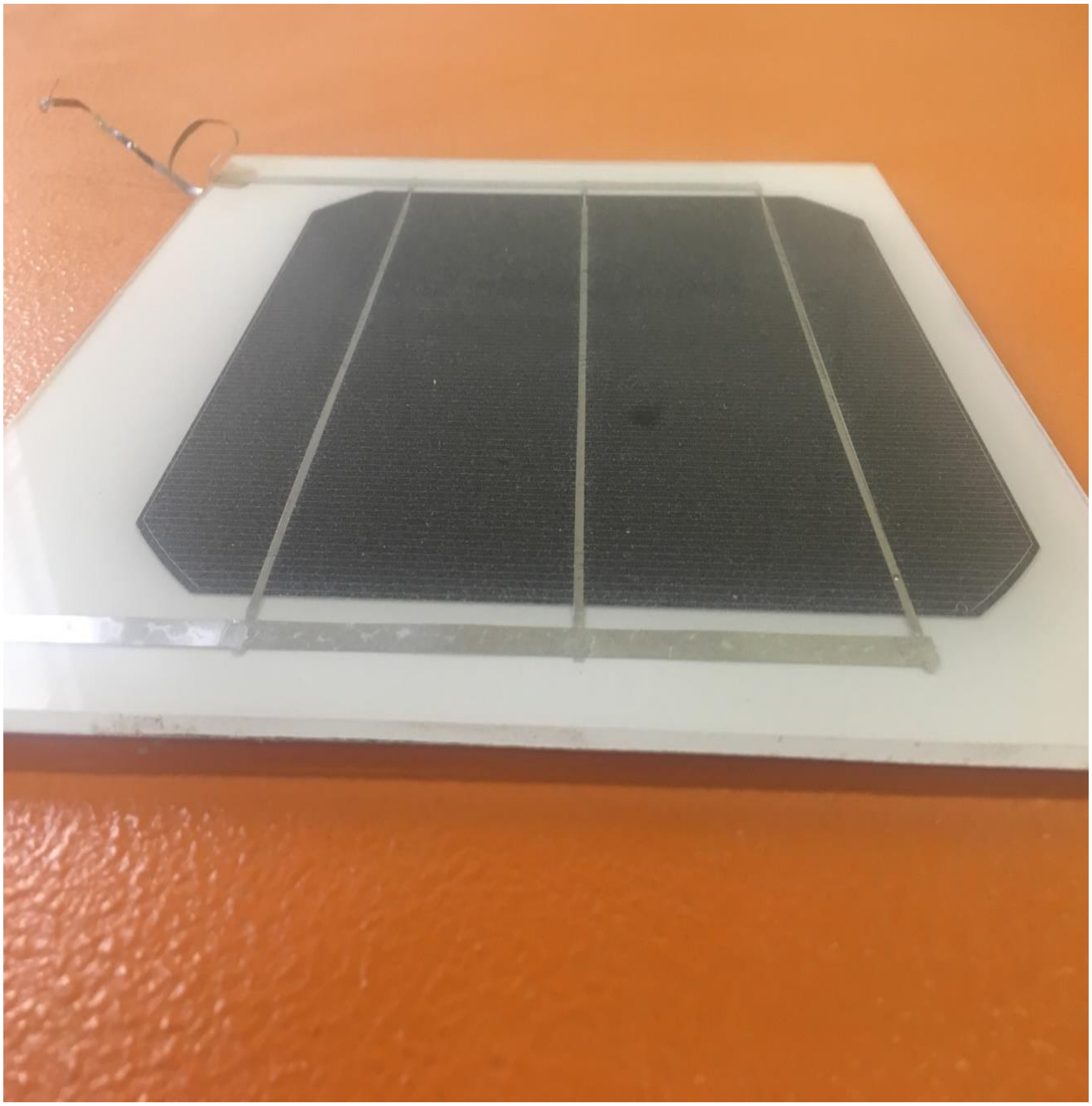

Figure 29 Dew Method Soiled Coupon

The above picture depicts a more uniform soiling deposition compared to the gravity method. The following graphs help us to illustrate the level of uniformity of the dew method on the monocrystalline silicon cell.

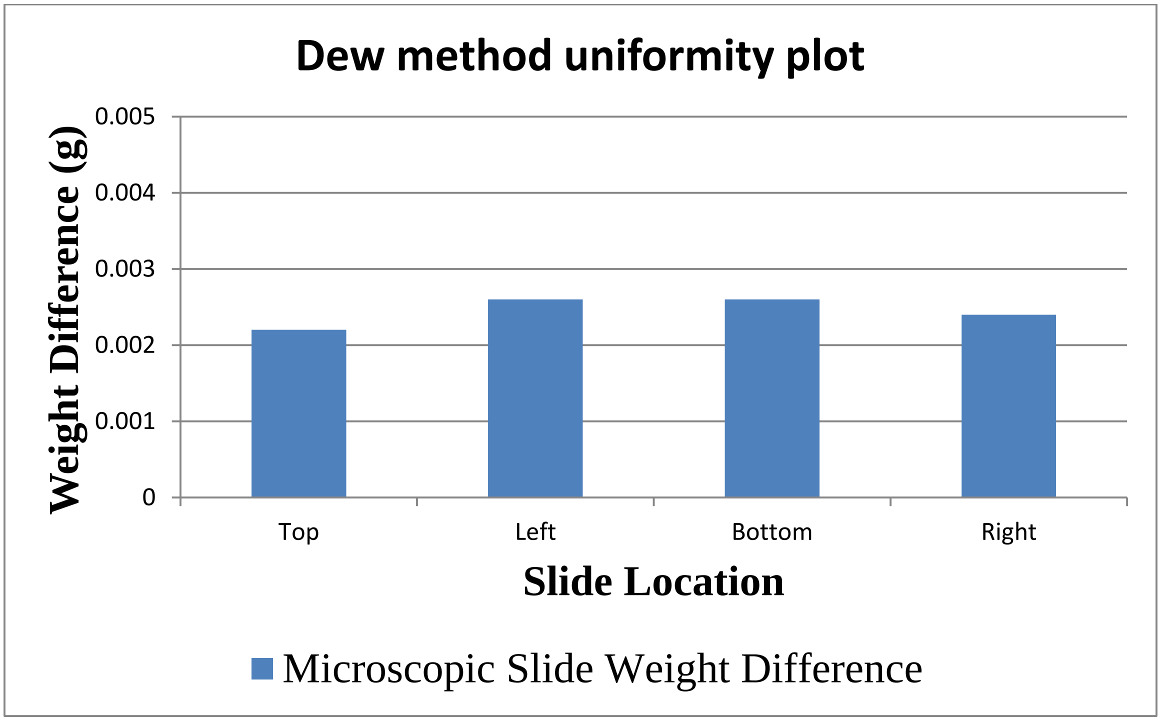

Figure 30 Dew Method Uniformity Bar Plot-1 Cycle-AZ Dust- 2 Grams

Fig-31 shows the close difference between the slide weights which indicates that the soil deposition is uniform. The standard deviation of the difference in weight of all four slides is 0.02% and the soil density varies from 1.2 to 1.4 g/m^2 which indicate a very good uniform deposition. This density is achieved by placing 2 grams of AZ dust in the dust vial.

4.1.3 Humidifier Method

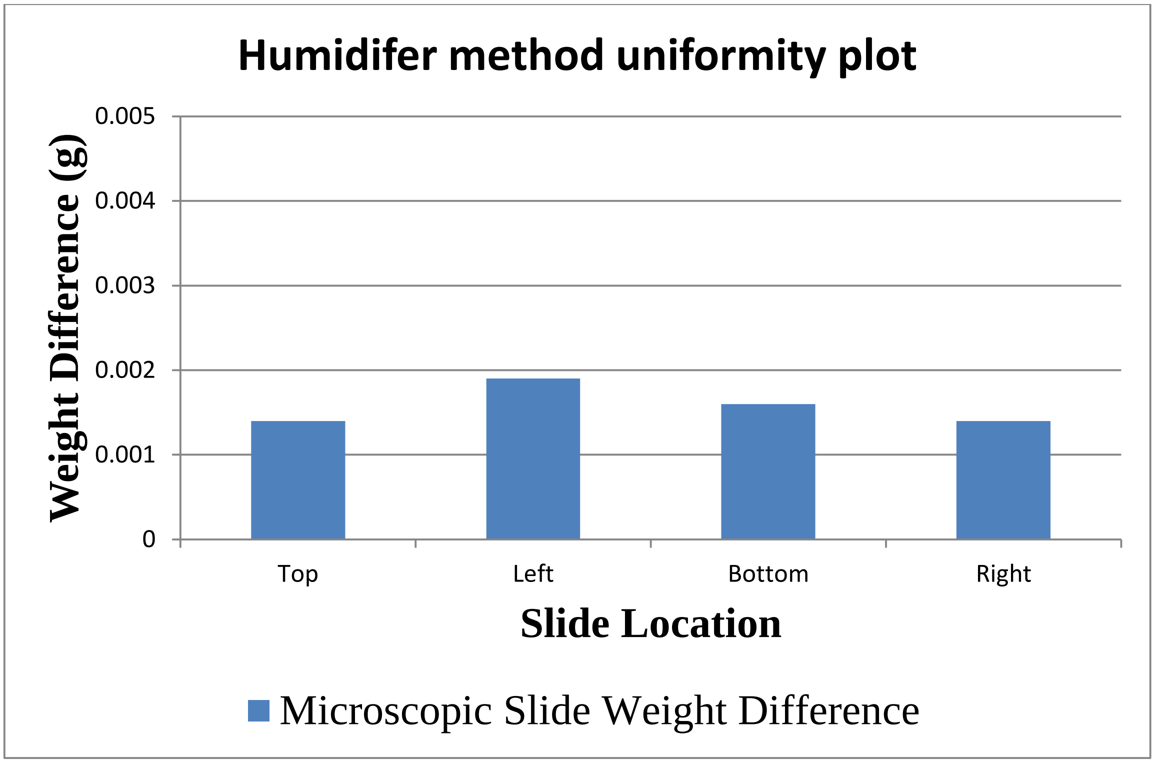

Figure 31 Humidifier Method Uniformity Bar Plot- 1 Cycle- AZ Dust-2 Grams

The slight variation in slide weight difference from the Fig-32 shows that the soil deposition is uniform. The standard deviation of the weight difference is 0.02%. The density value varies from 0.7 to 1 g/m^2. This density is achieved by placing 2 grams of AZ dust in the dust vial.

4.1.4 Comparison between Gravity, Dew and Humidifier Methods

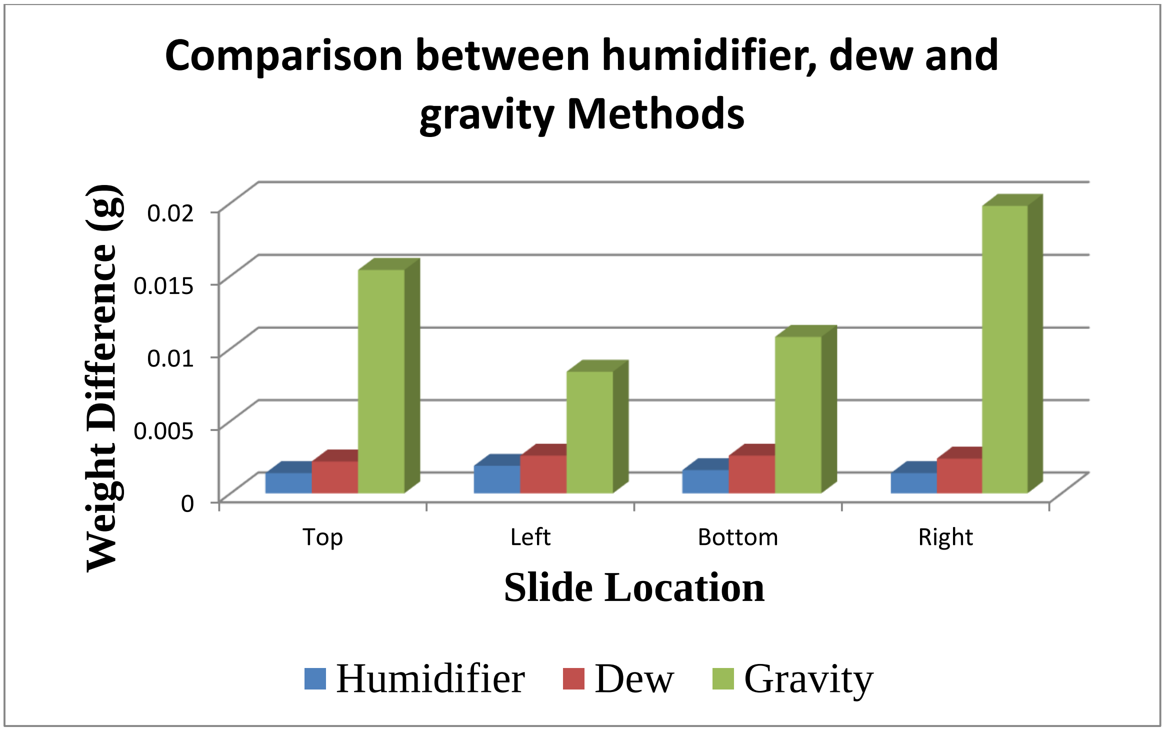

Figure 32 Comparison Plot Between Humidifier, Dew And Gravity Methods-1 Cycle AZ Dust-Monocrystalline Silicon

As discussed earlier, the gravity method soil deposition is non-uniform with standard deviation value of 0.44%. The dew and humidifier methods offer much more deposition uniformity which is the goal of this experiment. The standard deviation values are 0.02% (approx.). The uniformity these two methods offer are almost equal but the density values vary for both the methods. The humidifier method density value is an average of 0.85 g/m^2 and the dew method average density value is 1.3 g/m^2 for the same amount of dust (2 grams) used for the deposition method. This is because of the less condensation on the surface of the module which causes the particles to escape and lesser deposition rates because of the humidified air.

4.2 Soil Density and Uniformity Measurements for Polycrystalline Mini Module

4.2.1 Gravity Method

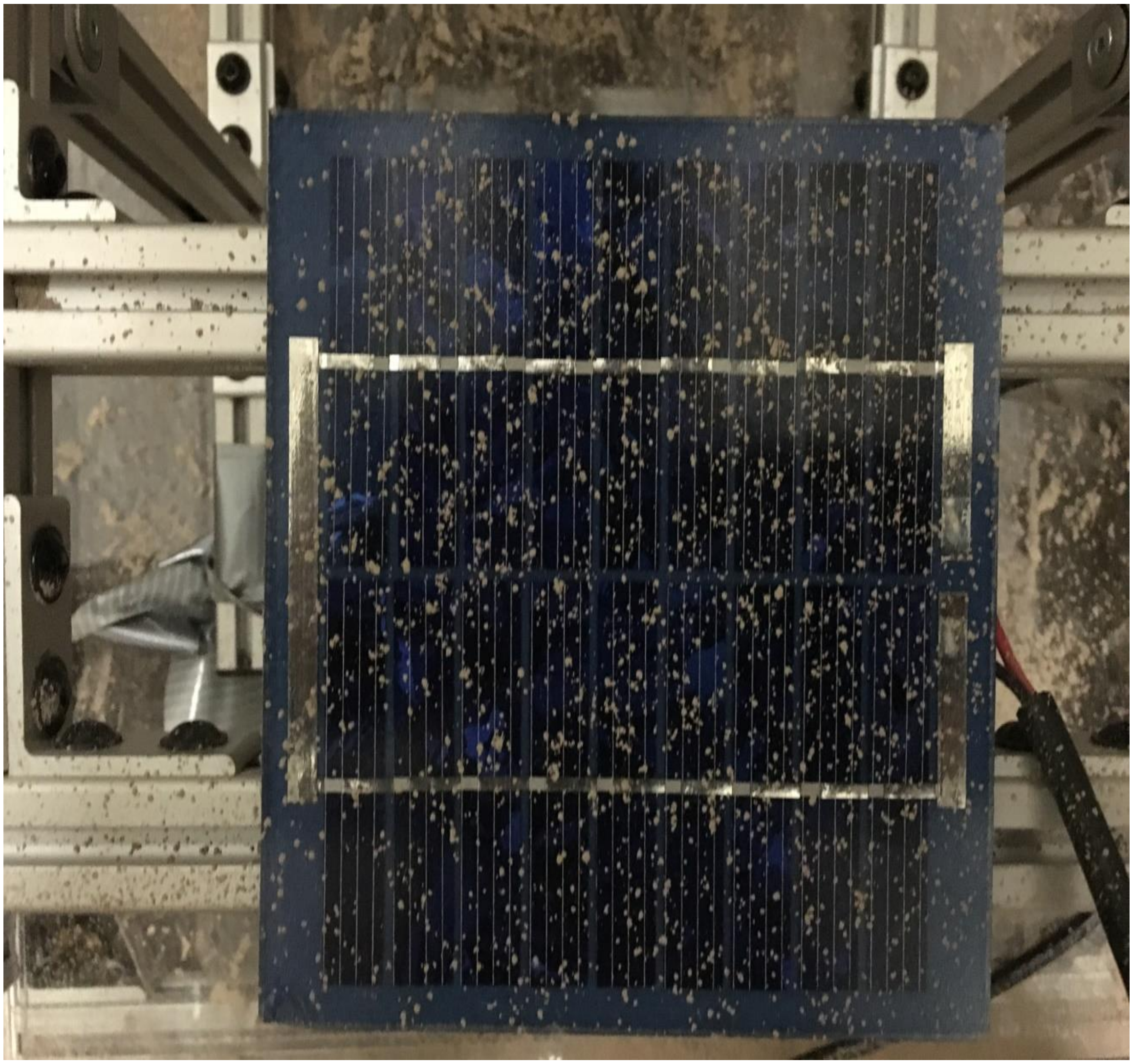

Figure 33 Gravity Method Soiled Coupon (Polycrystalline Silicon)

As in the case of monocrystalline silicon cell, it is clear from the picture that the gravity method does not offer uniform deposition. Following graphs gives us a clear picture of the effectiveness of this method.

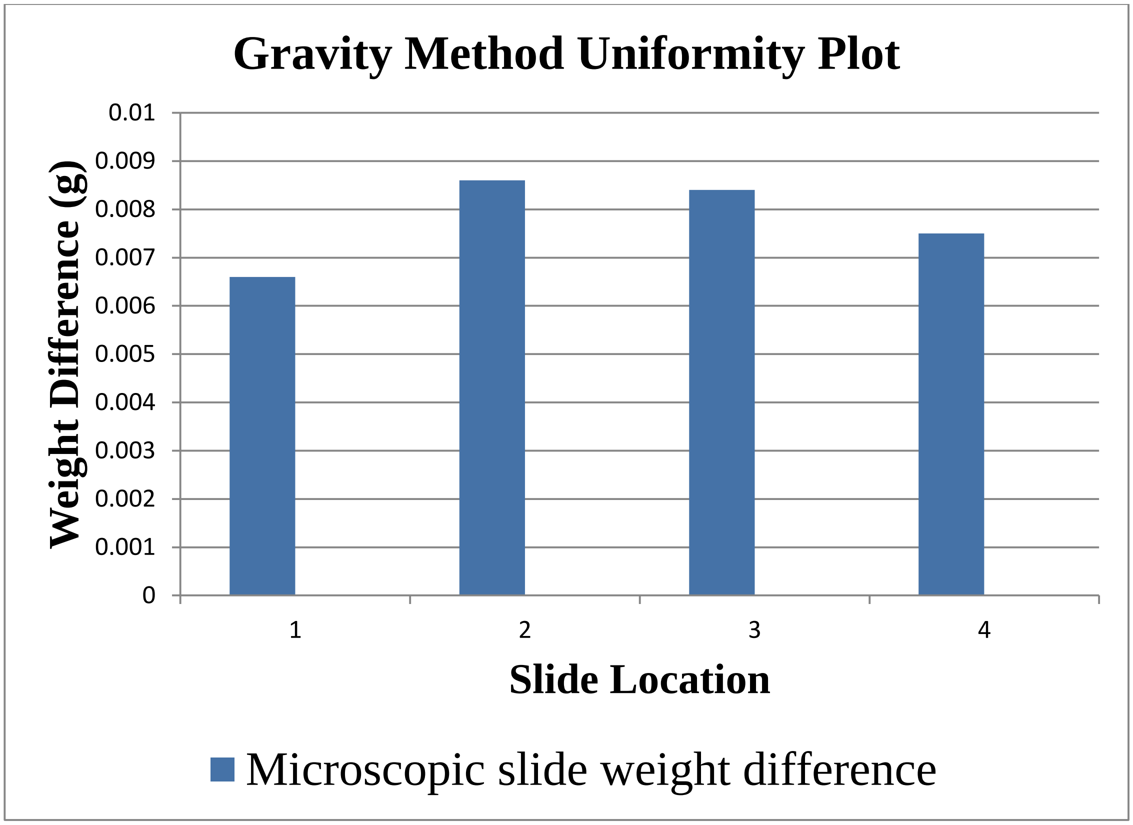

Figure 34 Gravity Method Uniformity Bar Plot (Polycrystalline Silicon)-AZ Dust- 1 Cycle

As it can be inferred from the above graphs, the soil deposition by gravity method is non-uniform. The standard deviation observed for the weight difference is 0.08%. The density values vary from 3.47 to 4.42 g/m^2 which show us that the deposition is not uniform.

4.2.2 Dew Deposition Method

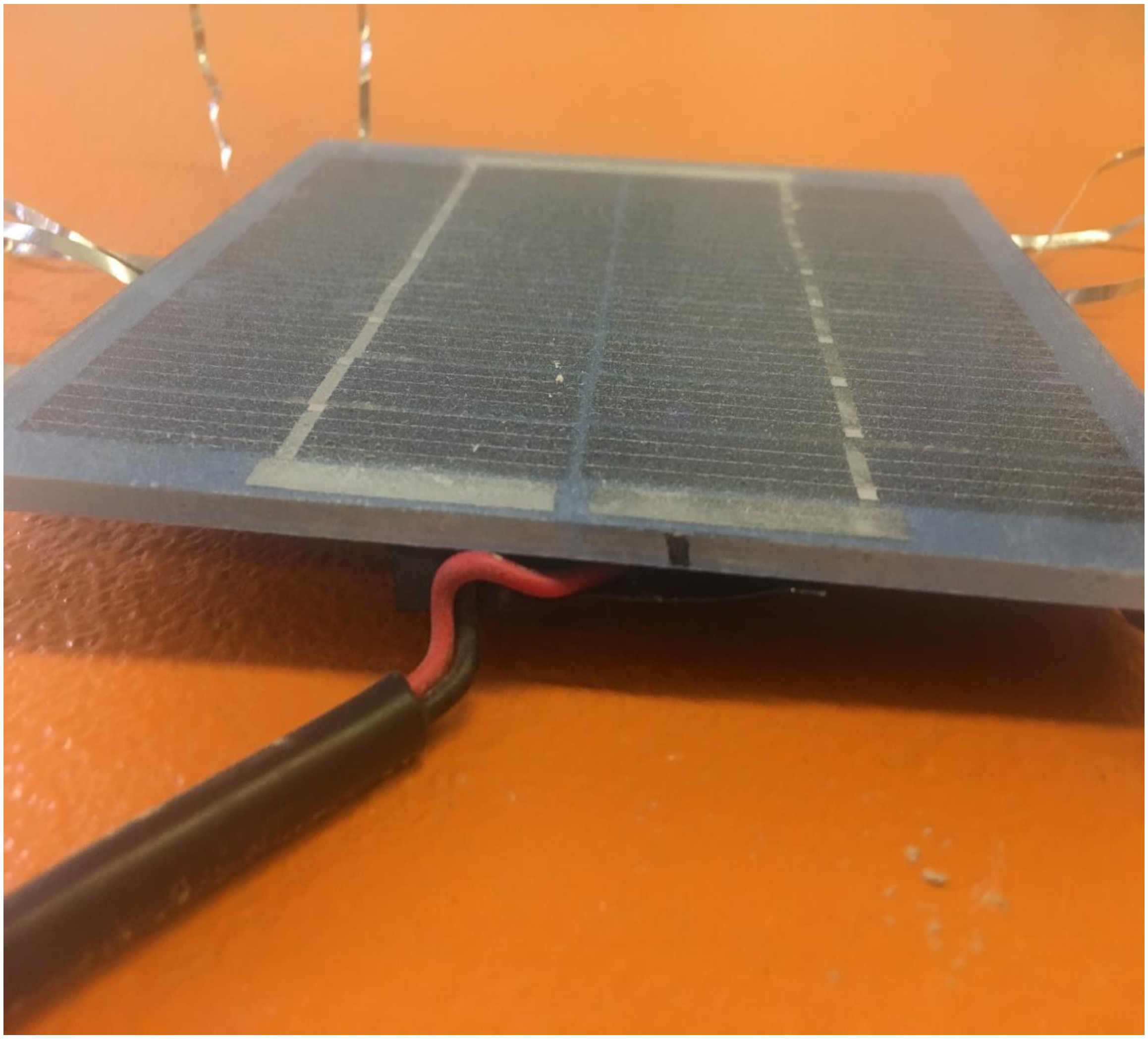

Figure 35 Dew Method Soiled Coupon (Polycrystalline Silicon)-1 Cycle-AZ Dust-2 Grams

The soil deposition when looked at visually shows uniformity across the module from figure-35. The module is placed in a freezer for one hour. AZ dust of 2 grams is placed in the dust vial and the dust cloud is formed by a burst of nitrogen gas onto the dust and is allowed to settle for 1 minute. Then it is baked for 1 hour in an oven at 65^0C. This deposition is done by placing the module at 0^0 tilt.

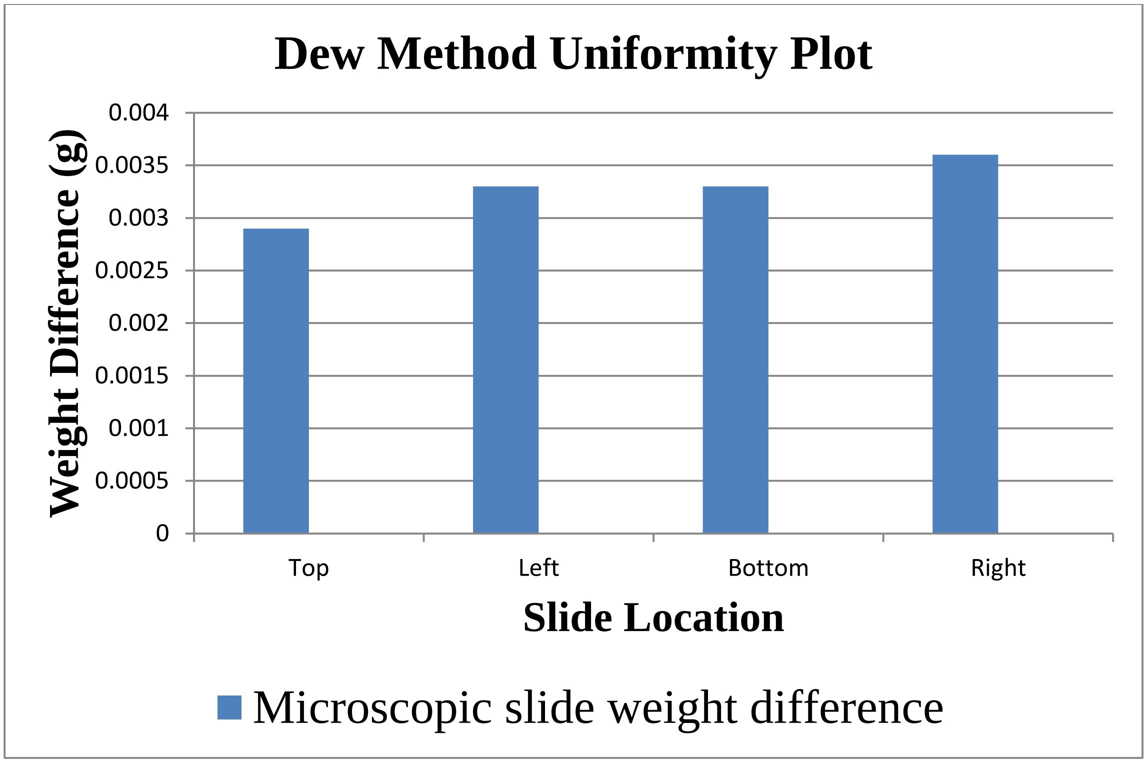

Figure 36 Dew Method Uniformity Bar Plot (Polycrystalline Silicon)-AZ Dust 1 Cycle-2 Grams

Fig-37 and Fig-36 clearly shows us that the soil deposition is uniform. The difference in weights (before and after soiling) of the microscopic slides is measured. The standard deviation of weights is 0.02%. The density value varies from 1.52 to 1.89 g/m^2.

4.2.3 Humid Deposition Method

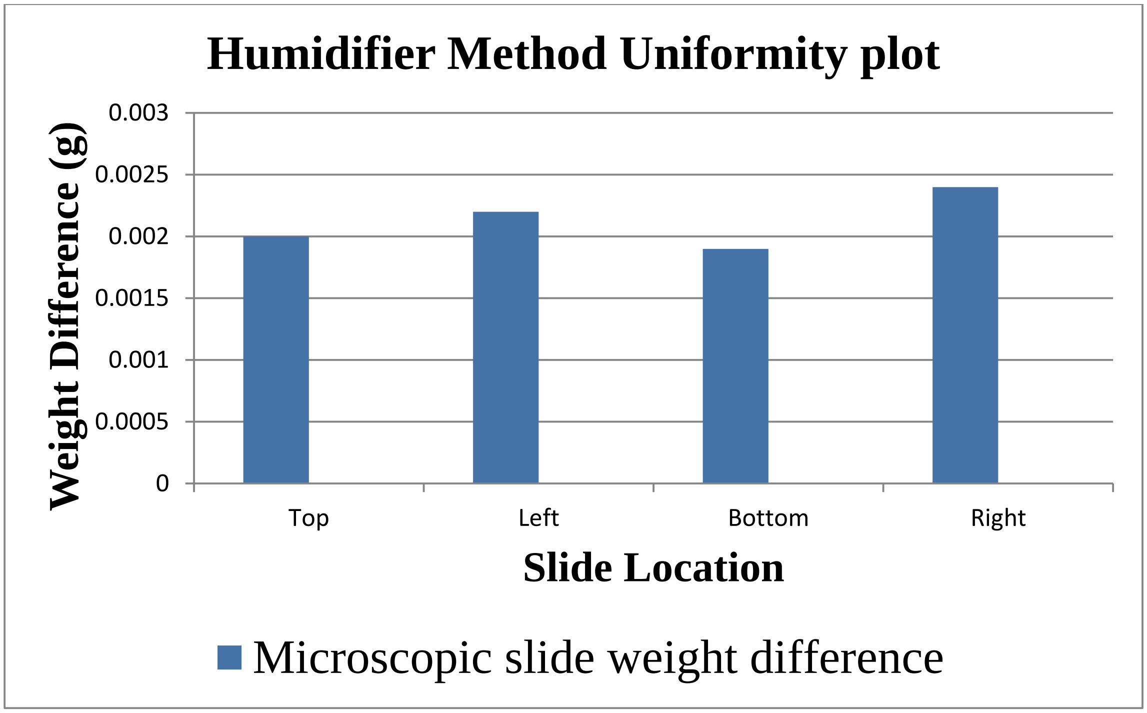

Figure 37 Humidifier Method Uniformity Bar Plot (Polycrystalline Silicon)-AZ Dust 1 Cycle-2 Grams

From the Fig-38 it is clear that the soil deposition is uniform in polycrystalline silicon test module. The process followed is similar to that of the dew method for measuring the weights. The standard deviation value is 0.02%. The density range is 1.0 to 1.26 g/m^2.

4.2.4 Comparison between Gravity, Dew and Humid Deposition Methods for a Poly Crystalline Mini Module

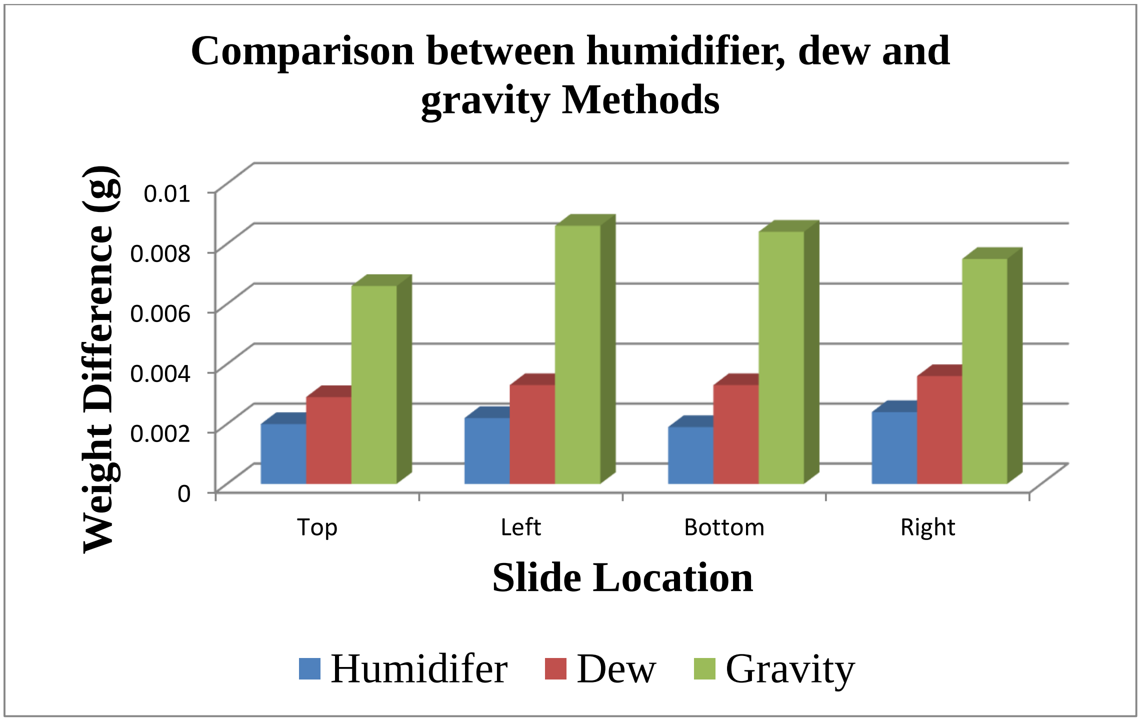

Figure 38 Comparison Plot Between Humidifier, Dew And Gravity Methods (Polycrystalline Silicon)-AZ Dust 1 Cycle

As discussed earlier, the gravity method soil deposition is non-uniform with standard deviation value of 0.08%. The dew and humidifier methods offer much more deposition uniformity which is the goal of this experiment. The standard deviation values are 0.02% (approx.) for both. The uniformity these two methods offer are almost equal but the density values vary for both the methods. The humidifier method density value is an average of 1.15 g/m^2 and the dew method average density value is 1.65 g/m^2 for the same amount of dust (2 grams) used for the deposition method. This is because of the less condensation on the surface of the module which causes the particles to escape.

4.3 Soil Uniformity Measurements Using Indoor Solar Simulator Isc Measurements on Single Cell Monocrystalline Coupon

After observing data from the previous section gravity method soil deposition is proved to be non-uniform, hence further experiments were not performed using that method. Dew deposition method was used for this experiment over humid deposition method to see considerable decrease in Isc values since the dew method soil density is high for every 2 grams of dust used. This experiment is done to prove that the uniform soil deposition using dew method can be achieved for modules at different angles (33^0 tilt in this case).

4.3.1 Isc Measurements for Reference Dust (AZ Road Dust)

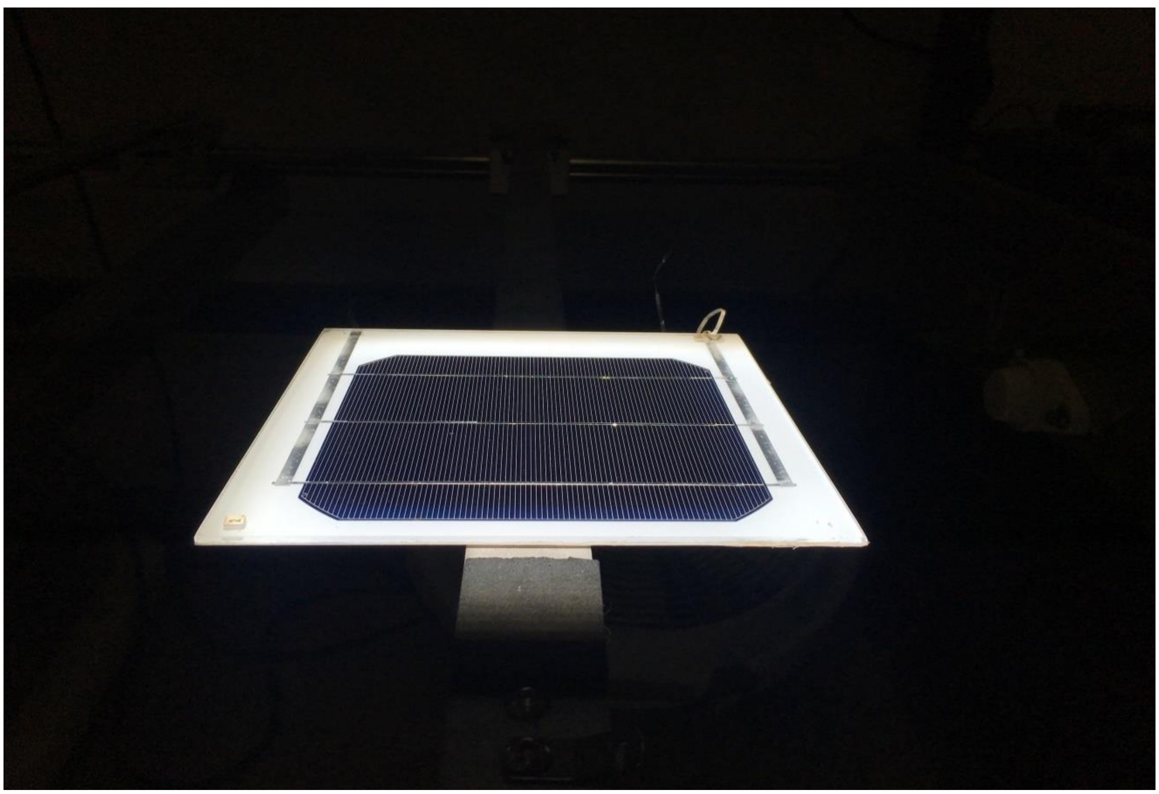

Figure 39 Monocrystalline Silicon in a Solar Simulator

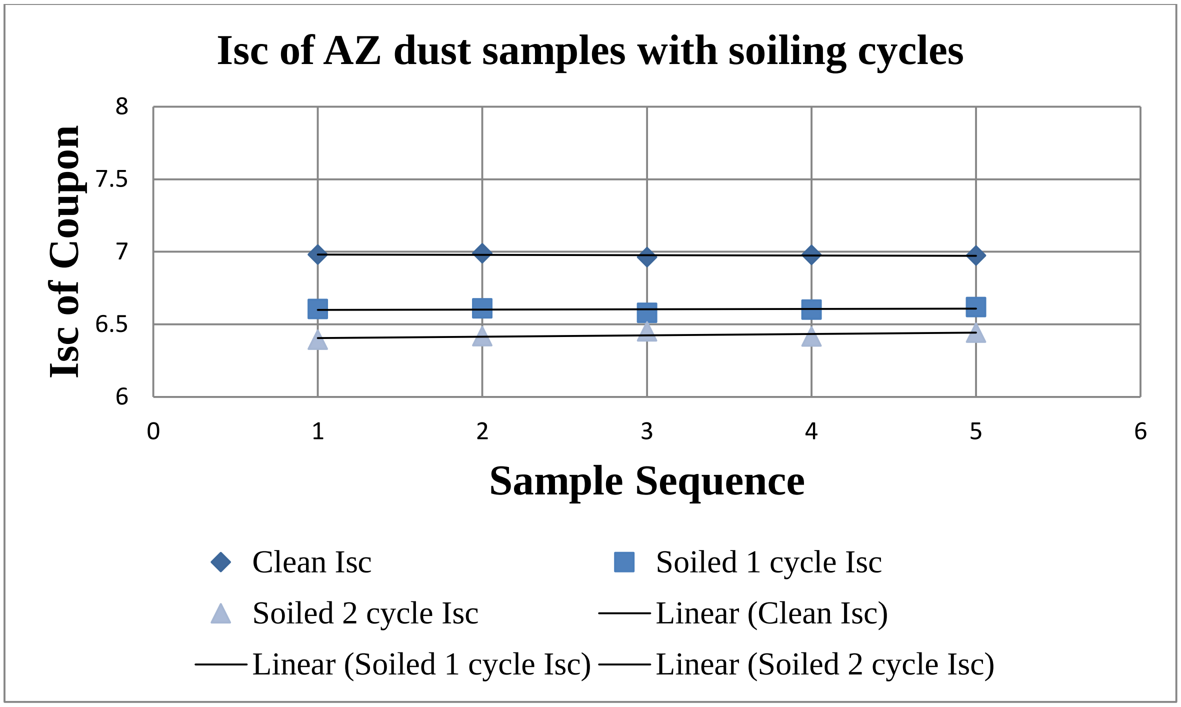

Figure 40 Isc Plot of AZ Dust on Monocrystalline Coupon-2 Cycles-5 Test Sequences-2 Grams Dust for Each Cycle

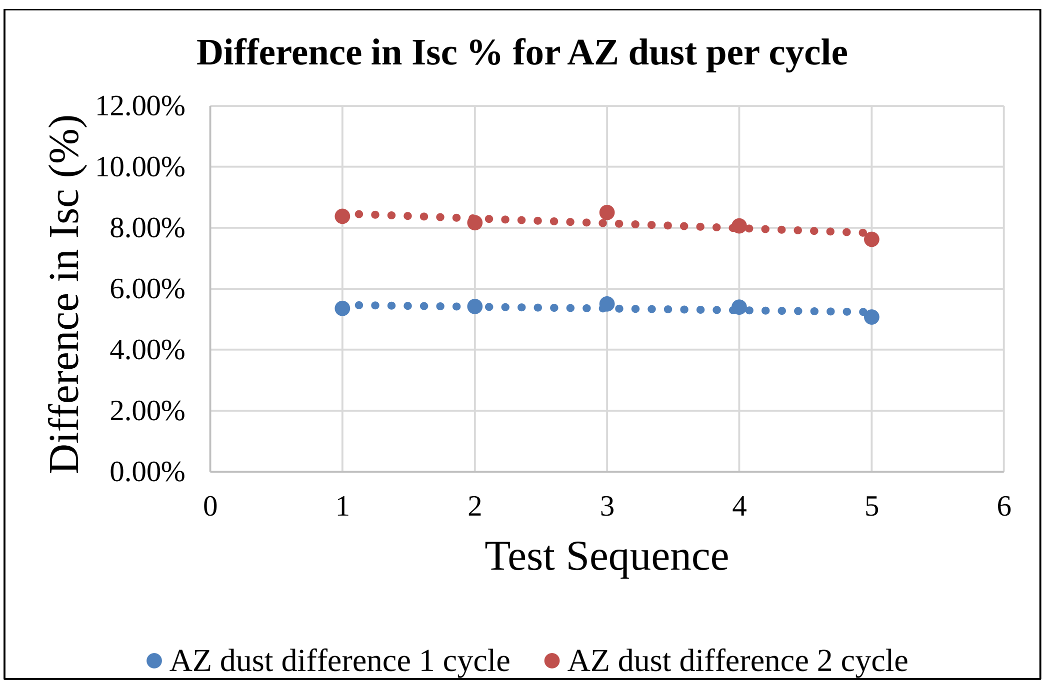

Figure 41 Isc (%) Difference Plot of Dew Method AZ Dust-2 Cycles-5 Test Sequences-2

Grams Dust for Each Cycle

In all the 5 sequences the Isc values are consistent for Clean, 1 soil cycle and 2 soil cycles. This shows the uniform deposition of soil. The average losses for consecutive soiling cycles are around 5.35% and 7.91%. The Isc decrease is consistent across 2 soil cycles which shows the repeatability of the deposition technique.

4.3.2 Isc Measurements for Collected Dust at ASU-PRL, Mesa

The results for the experiment done using the dust collected from PV module surface are shown below. This is to show the versatility and repeatability of the technique.

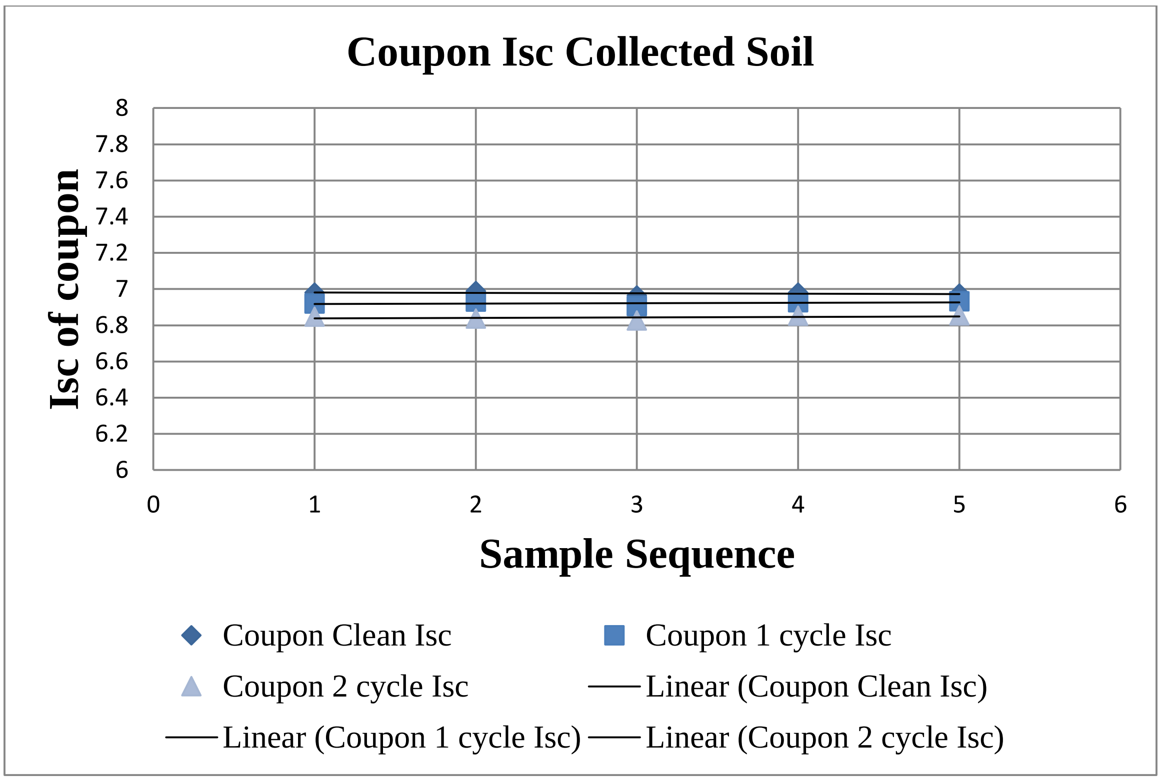

Figure 42 Isc of Coupon Collected Soil-2 Cycles-5 Test Sequences-2 Grams Dust for each Cycle

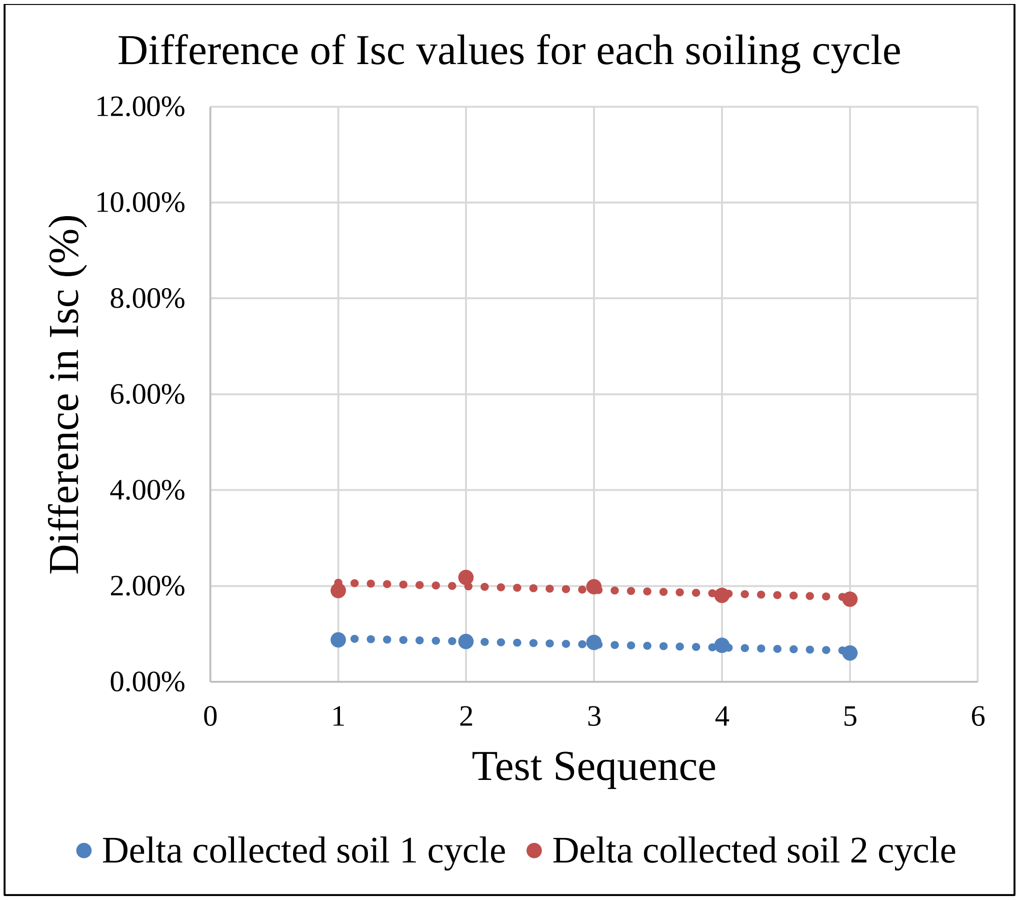

Figure 43 Isc (%) Difference Plot of Dew Method Collected Soil-2 Cycles-5 Test Sequences-2 Grams Dust for each Cycle

In all the 5 sequences the Isc values are consistent for Clean, 1 soil cycle and 2 soil cycles for the collected dust. The average losses for consecutive soiling cycles are around 0.77% and 0.91%. This shows the uniform deposition. The Isc losses however dropped only slightly which means the deposition density is less. This could be attributed to the soil type.

4.4 Comparison of Difference in Isc Percentages for AZ and Collected Soil

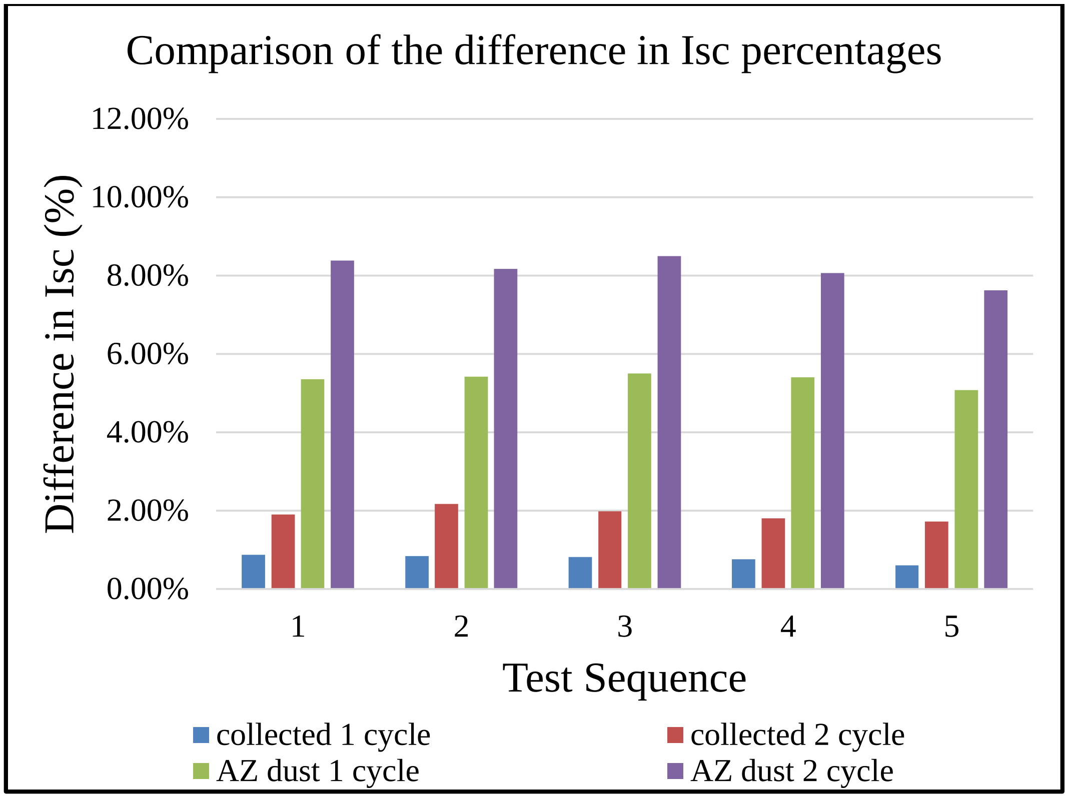

Figure 44 Comparison of the Isc Drop for AZ Dust and Collected Soil- Approximately 2 Grams Of Soil placed in the Soil Dispersion Chamber and around 1 Minute of Settling Time with Soil Density of around 1.5 g/m^2 Per Cycle

From the above figure it is clear that the Isc drop is seen as the soiling level increases. The interesting thing we can see is the AZ dust cycle has seen more Isc drop than the collected soil which could be attributed to the larger particle size of the AZ dust. Due to the larger particle size more light is either absorbed or reflected which causes the Isc drop. Even though the Isc drop varies among different soil types it is consistent across all the samples. This shows that the process is repeatable for any soil type.

4.5 Dew Method Soil Deposition on Glass Coupons

Using the indoor solar simulator transmittance values are calculated for the glass coupons to get the uniformity data and repeatability of the technique.

4.5.1 Uniformity Measurements of 5 Cycle Deposition for AZ Road Dust

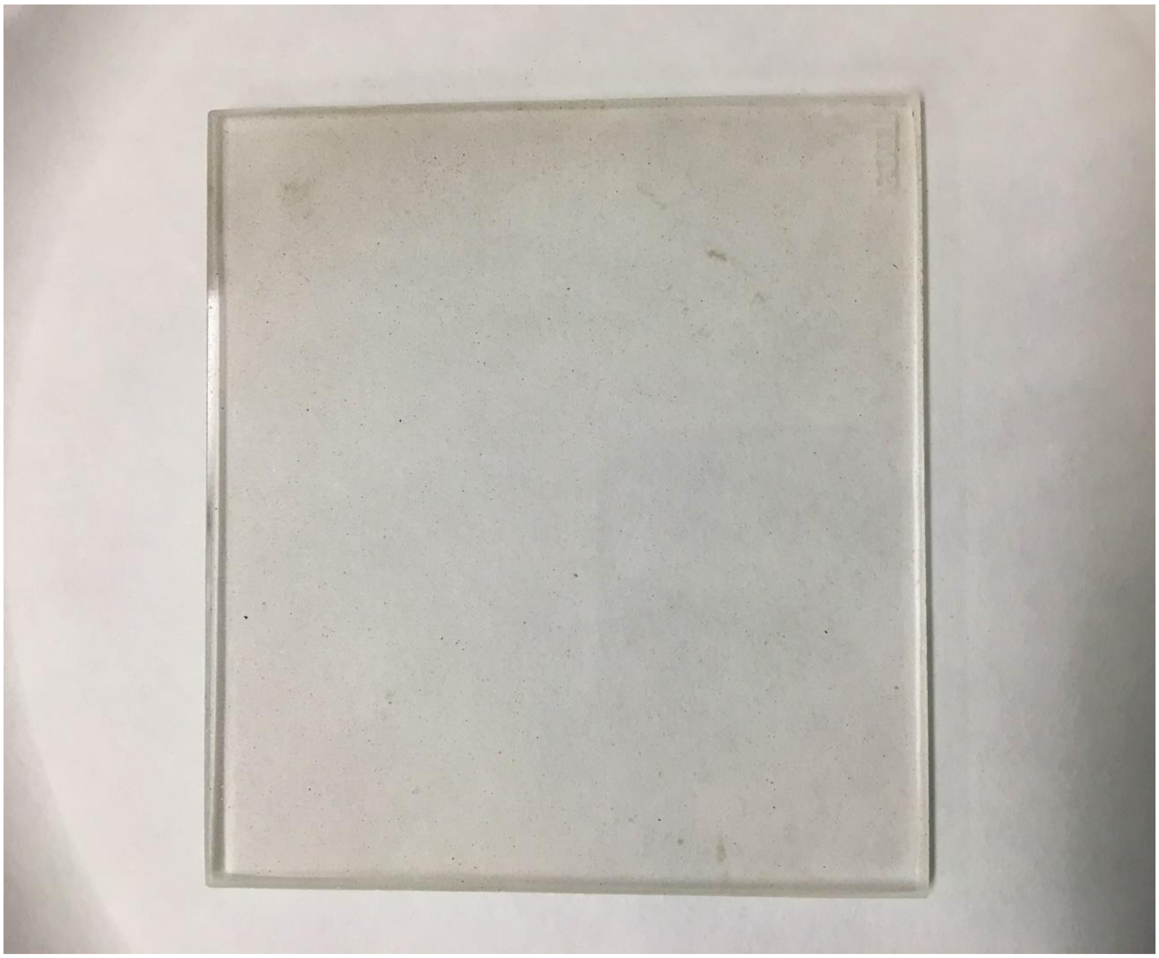

Figure 45 AZ Dust 5 Cycle Soiled Glass Sample

5 Cycle Soil density = 7.1 g/m^2 1 Cycle Soil density = 1.42 g/m^2 (approx.)

Reference cell = 77.2 mv   Bare Glass = 72.1 mv

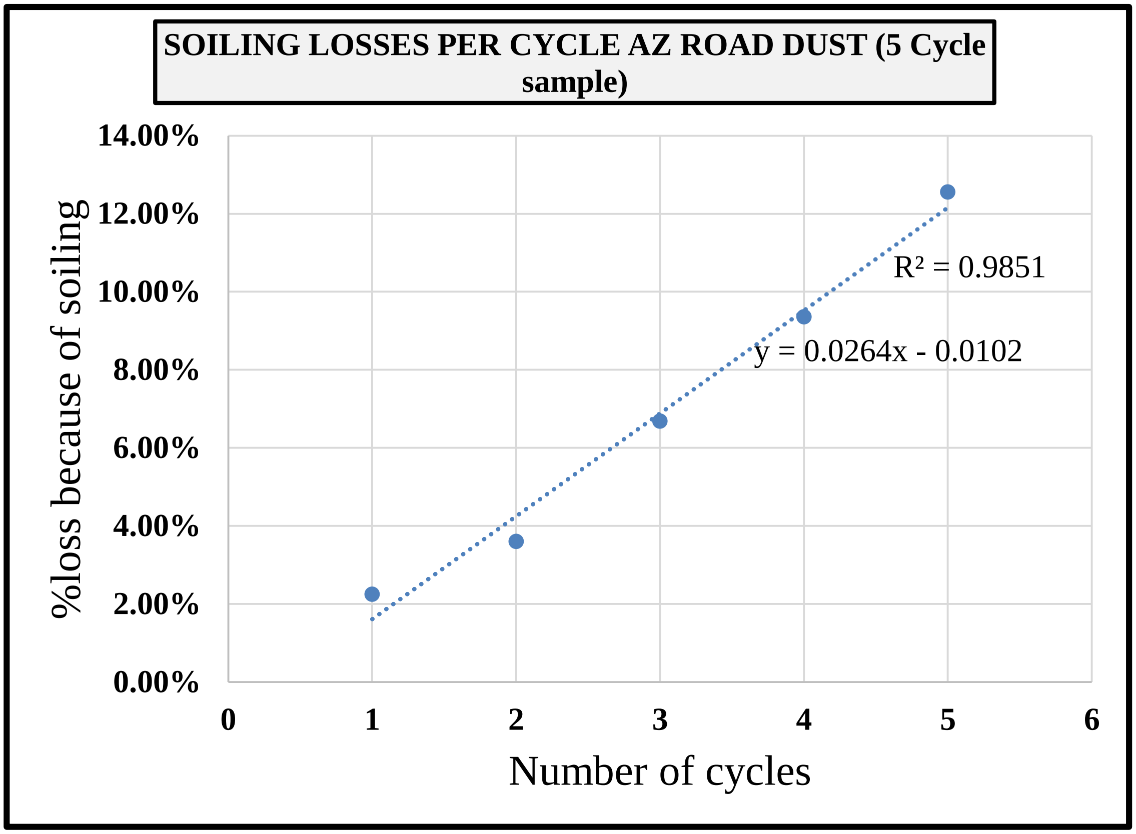

Figure 46 AZ Dust 5 Cycle Glass Samples Soiling Losses

The above graph clearly suggests that the % loss of transmittance which in turn caused the % loss in voltage is consistent which indicates that the soil deposition is uniform.

4.5.2 Uniformity Measurements of 10 Cycle Deposition for Collected Soil

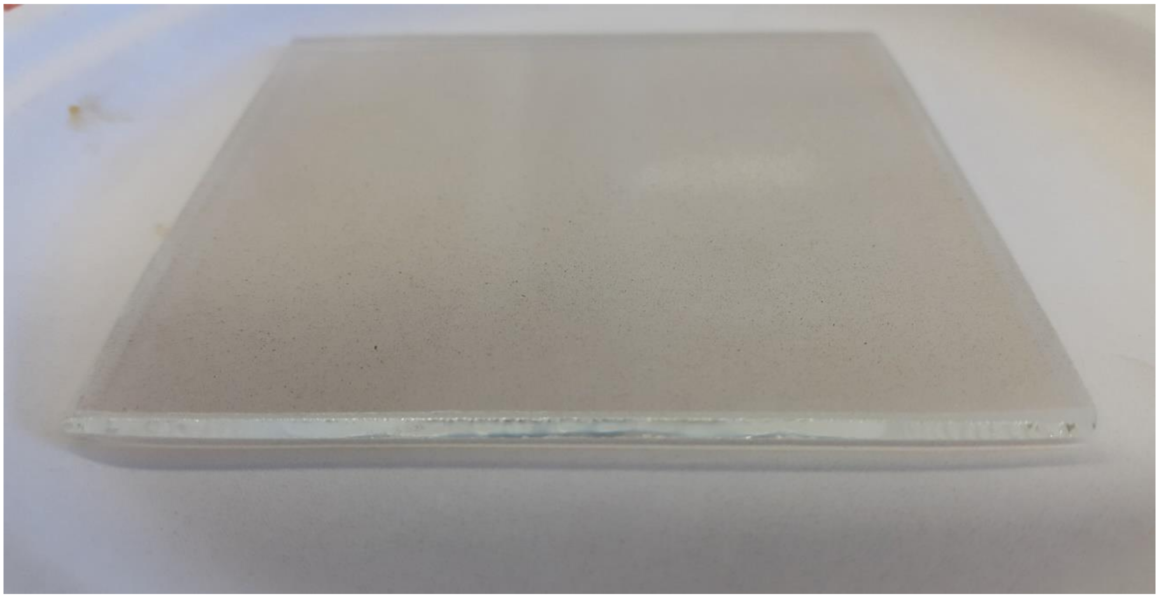

Figure 47 Collected Soil 10 Cycle Soiled Glass Sample

10 Cycle Soil density = 15.4 g/m^2 1 Cycle Soil density = 1.48 g/m^2 (approx.)

Reference cell = 79.7 mv   Bare Glass = 74.4 mv

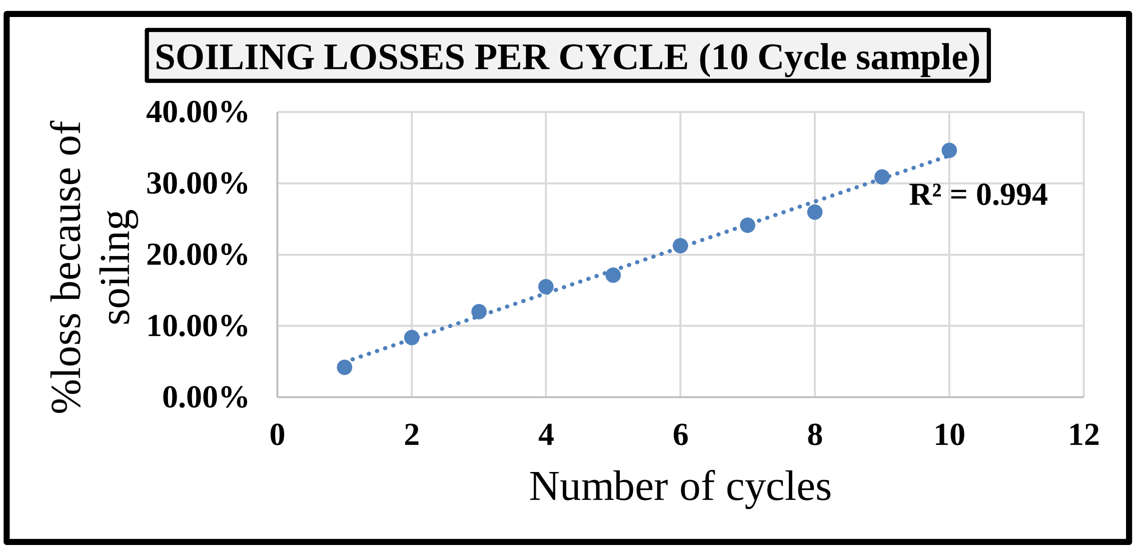

Figure 48 Collected Soil 10 Cycle Glass Samples Soiling Losses

Consistent % loss in voltage means that the deposition is uniform. The density value is in correlation with the 5 cycle deposition which means that the technique is repeatable.

4.5.3 Uniformity Measurements of 15 Cycle Deposition for Collected Soil

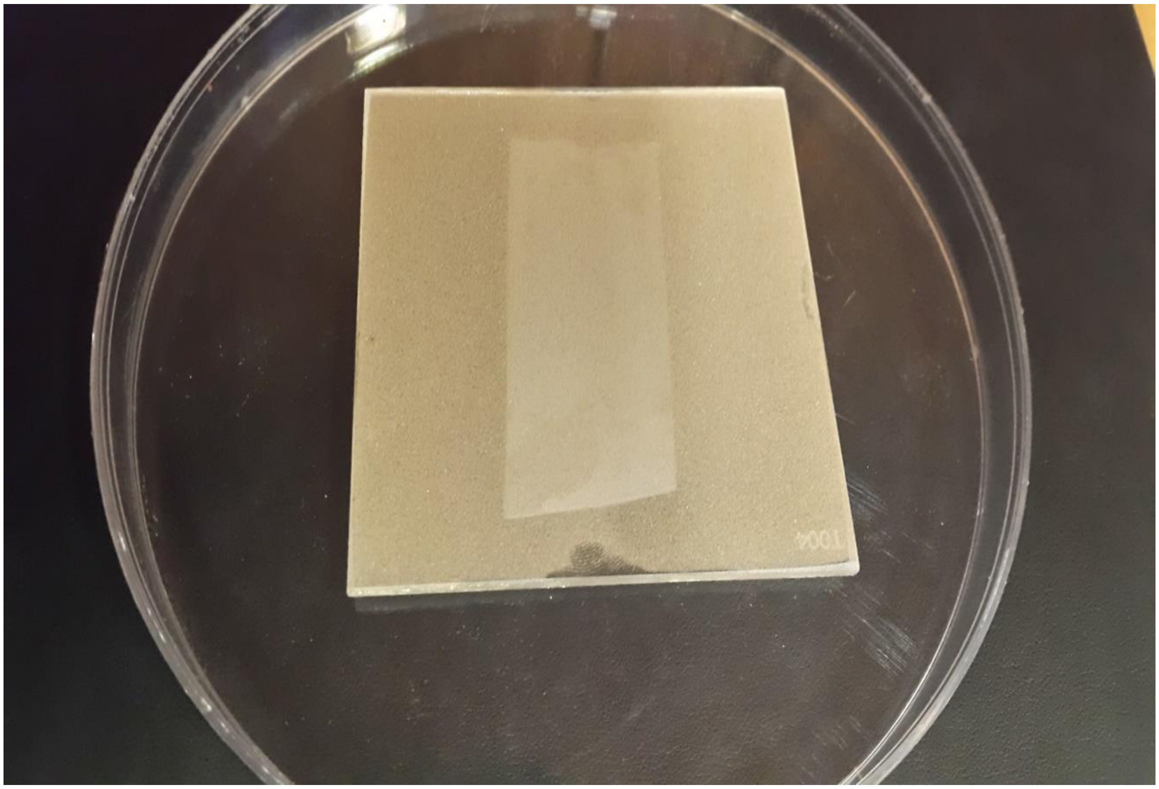

Figure 49 Collected soil 15 cycle soiled glass sample

15 Cycle Soil density = 22.3 g/m^2 1 Cycle Soil density = 1.48 g/m^2 (approx.)

Reference cell = 77.3 mv

Bare Glass = 72.1 mv

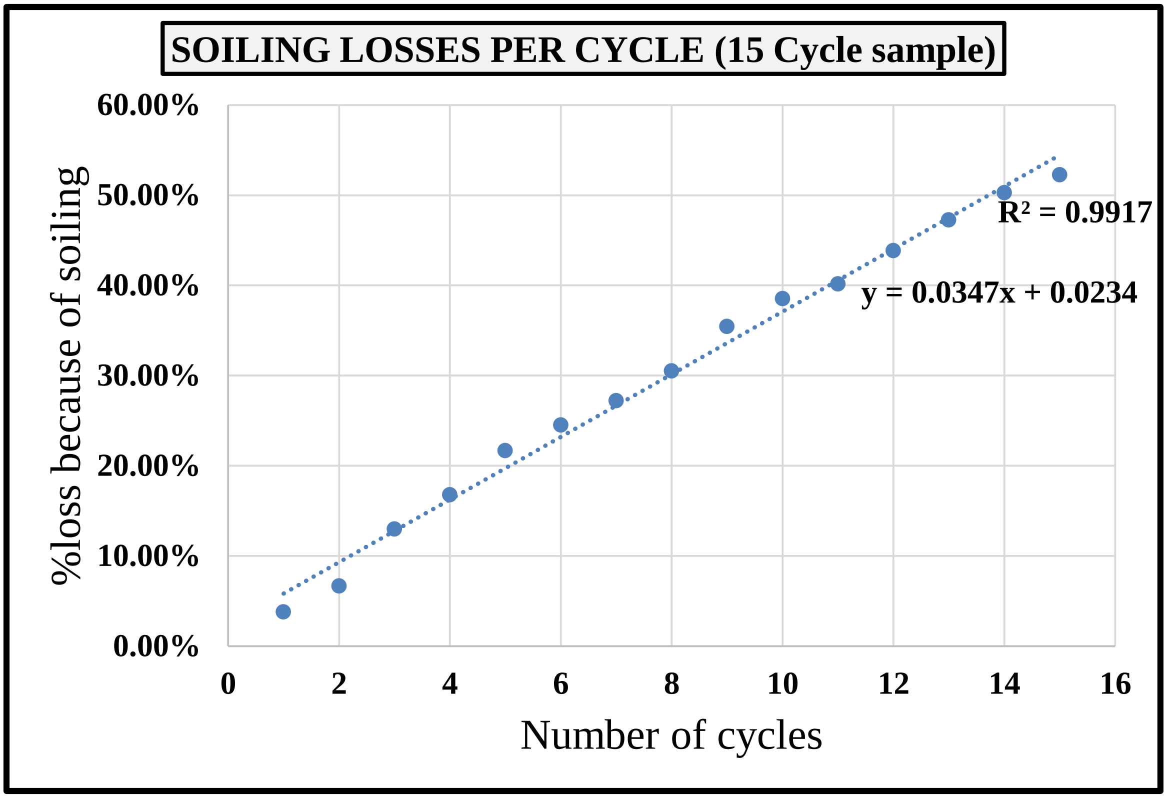

Figure 50 Collected Soil 15 Cycle Glass Samples Soiling Losses

Consistent % loss means that the deposition is uniform. With 1.48 g/m^2 average density value for different cycle soil deposition it can be inferred that the deposition technique is repeatable.

4.6 Glass Coupons Transmittance Losses Comparison

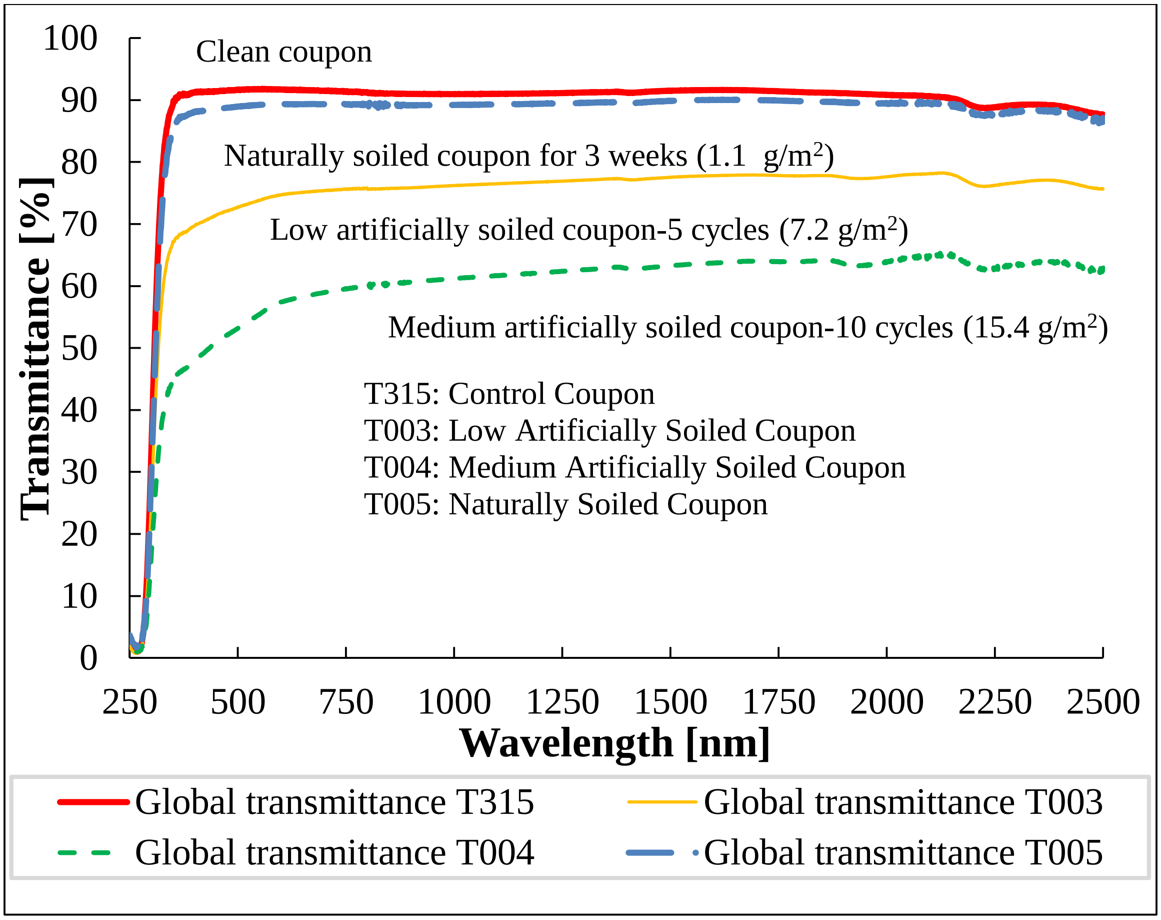

Figure 51 Glass Coupons Tranmittance Loss Comparison

From the above figure it is clear that as the soil density increases the transmittance value reduces. More soil density means that the soil particles reflect more wavelengths of light causing the scattering phenomenon. The interesting thing observed is for a naturally soiled coupon at 33^0 tilt, it takes 3 weeks to get 1.1 g/m^2 soil density but by using the dew or humidifier methods used in this thesis we can deposit about 1.4 g/m^2 soil density at 33^0 tilt in 2 hours (only1 min to deposit soil if we remove the freezing and baking parts of the experiment).

4.7 Gravity Method

Merits:

- One of the main advantages of the gravity method is the sand which is collected from the PV modules can be deposited directly onto the mini module and coupon without any changes to the soil composition. Since the dust collected is already deposited onto the modules by natural phenomena, this method helps us to deposit it directly in a short period of time.

Limitations:

- The difficulty we faced during this process is achieving the uniform deposition of the soil on the mini module. The dust deposition is not uniform across the module because of the clumps formed in the sand.
- The deposition should be done on the module only at horizontal position which is not correct representation for the all the modules installed.

4.8 Dew Deposition Method

Merits:

- The uniformity of dust achieved with this technique is much better than the gravity based method.
- This method can be done with the test module placed at any angle.
- The process is repeatable for any soil type.

Limitations:

- This method only simulates hot and dry climate. It cannot be used if the soiling is to be done in a humid environment.

4.9 Humid Deposition Method

Merits:

- The uniformity achieved through this method is on par with the dew method.
- This method can be used at any climatic conditions since the humidity levels can be controlled.

Limitations:

- The uniform soil deposition takes time; hence the need for more soiling cycles to achieve required soil density.

5 CONCLUSIONS

The main objective of this thesis is to deposit soil using artificially developed methods uniformly onto crystalline silicon coupons and mini modules. This is achieved by three methods namely Gravity, Dew and Humid deposition methods. These methods are designed and fabricated such that they closely represent the natural soil deposition process. Once the uniform deposition is achieved, this thesis looks into various factors such as tilt angle and repeatability

5.1 Microscopic Slide Method

5.1.1 Gravity Deposition Method

- The soil deposition achieved using gravity method was not uniform.
- The standard deviation of the difference in weights of microscopic slides used for uniformity measurements are 0.44% for monocrystalline silicon coupon and 0.08% for polycrystalline silicon mini module which shows non-uniform deposition.
- The density values are not consistent which are varying from 4.4 to 8.1 g/m^2 for monocrystalline silicon coupon and 3.47 to 4.42 g/m^2 for polycrystalline silicon module.
- This method is limited to deposition only at 0^0 tilt.

5.1.2 Dew Deposition Method

- The standard deviation achieved for both mono and polycrystalline silicon are 0.02% which indicates uniform soil deposition

- The density varies from 1.2 to 1.4 g/m^2 for monocrystalline silicon and 1.52 to 1.89 g/m^2 for polycrystalline silicon.

5.1.3 Humid deposition method

- The standard deviation values for humidity method are similar to that of dew method at 0.02% for both mono and polycrystalline silicon.
- The density value varies from 0.7 to 1 g/m^2 for monocrystalline silicon and 1 to 1.26 g/m^2 for polycrystalline silicon.

The uniformity of deposited soil is practically the same for both dew and humid methods but the density range of the humid method is less than that of the dew method because of the slower deposition rates caused due to moisture present in the atmosphere for humid method. From figure 50 we observed that for a naturally soiled coupon at 33^0 tilt, it takes 3 weeks to get 1.1 g/m^2 soil density but by using the dew or humidifier methods used in this thesis we can deposit about 1.4 g/m^2 soil density at 33^0 tilt in 2 hours (only1 min to deposit soil if we remove the freezing and baking parts of the experiment).

5.2 Isc Measurement Method on Monocrystalline Silicon and Glass Coupons

The Isc measurement using dew method experiment is done to determine if the soil uniformity can be achieved at different tilt angles and soil types. The monocrystalline silicon and glass coupons are placed at 33^0 tilt angle for the purposes of this experiment.

- The results obtained from this experiment shows that there is consistent decrease in Isc losses for 1st and 2nd cycle for both collected soil and AZ dust. This proves that the soil deposition is uniform and the process is repeatable for different soil types and tilt angles. One conclusion we made from this is the AZ dust causes more Isc drop than the collected soil (Mesa, AZ) because of the bigger particle size.

- The collected soil is deposited on the glass coupons for 5 cycles and AZ dust for 10 and 15 cycles using dew method. The 5 cycle collected soil has an average density of 1.42 g/m^2 for each cycle, 10 cycle AZ dust has average value of 1.48 g/m^2 for each cycle and 15 cycle AZ dust has average value of 1.48 g/m^2 for each cycle. This proves that the soiling density for dew method is consistent and the method is repeatable. For humidity method due to time constraints the repeatability measurements

5.3 Recommendations

The gravity method uniformity can be improved by more accurate design of the soil dispensing system, varying the mesh screen size. This method can be more accurately correlated to the natural phenomena by introducing wind factor for previously characterized soil and also in humid environment. The dew method and humid method can be further improved by extrapolating this model for full sized PV modules with temperature and humidity controls inside the chamber. Furthermore, performing dew and humidifier experiments for different soil types and different climatic conditions would prove the reproducibility of the methods across different testing labs.

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APPENDIX A

SOIL CHARACTERIZATION DATA

PTI POWDER TECHNOLOGY INC.

PRODUCT LIST PP2G4

ISO 12103-1 ARIZONA TEST DUST CONTAMINANTS A2 FINE AND A4 COARSE GRADES

TYPICAL CHEMICAL ANALYSIS

Chemical	% Of Weight	Chemical	% Of Weight
SiO_2	68 - 76	CaO	2.0 - 5.0
Al_2O_3	10 - 15	MgO	1.0 - 2.0
Fe_2O_3	2 - 5	TiO_2	0.5 - 1.0
Na_2O	2 - 4	K_2O	2.0 - 5.0

*Loss on Ignition 2 – 5%

ISO TEST DUST PARTICLE SIZE DISTRIBUTIONS BY VOLUME %

SIZE (μm)	ISO 12103-1, A2 Fine (% less than)	ISO 12103-1, A4 Coarse (% less than)
1	2.5 – 3.5	0.6 – 1.0
2	10.5 – 12.5	2.2 – 3.7
3	18.5 – 22.0	4.2 – 6.0
4	25.5 – 29.5	6.2 – 8.2
5	31.0 – 36.0	8.0 – 10.5
7	41.0 – 46.0	12.0 – 14.5
10	50.0 – 54.0	17.0 – 22.0
20	70.0 – 74.0	32.0 – 36.0
40	88.0 – 91.0	57.0 – 61.0
80	99.5 – 100	87.5 – 89.5
120	100	97.0 – 98.0
180	-	99.5 – 100
200	-	100

Figure 52 AZ Dust Chemical Composition and Particle Size

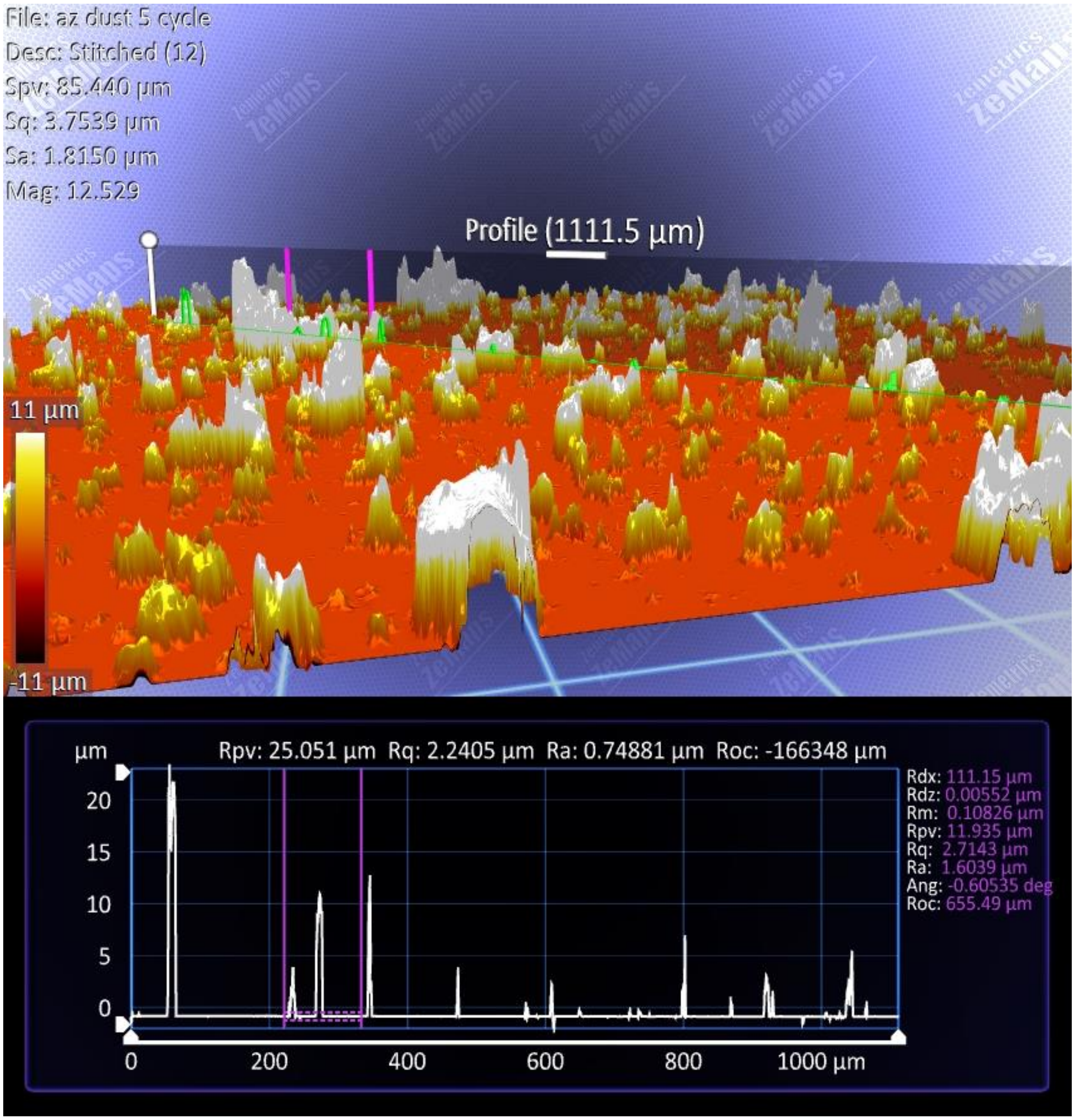

Figure 53 Surface Image of AZ Dust 5 Cycle Sample- Approximately 2 Grams of Sample Soil kept In Soil Dispersion Chamber and Approximately 1 Minute of Settling Time with Soil Density of around 1.4 g/m^2 Per Cycle

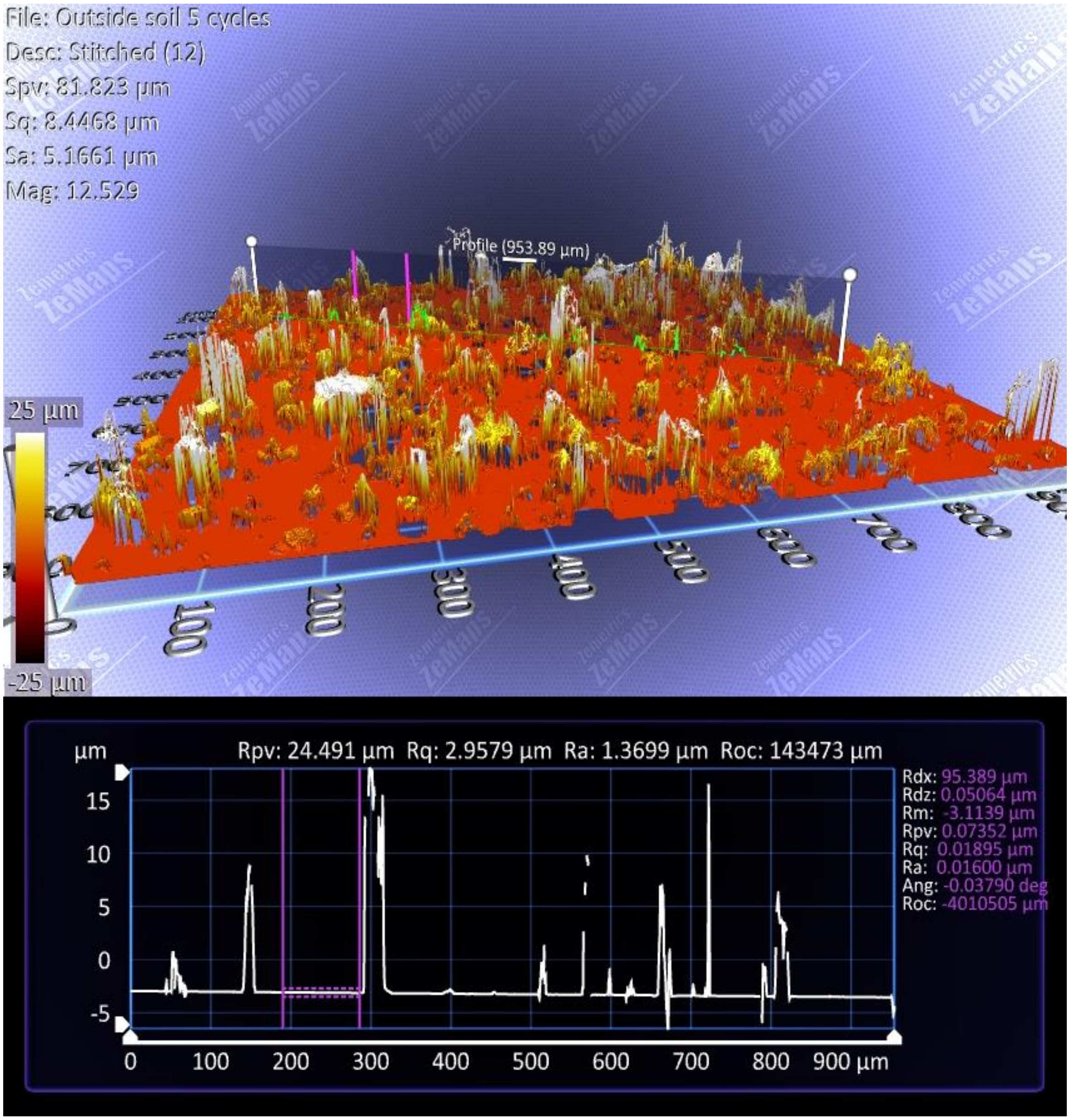

Figure 54 Surface Image of Mesa Collected Soil 5 Cycle Sample- Approximately 2 Grams of Sample Soil kept in Soil Dispersion Chamber and Approximately 1 Minute of Settling Time with Soil Density of around 1.4 g/m^2 Per Cycle

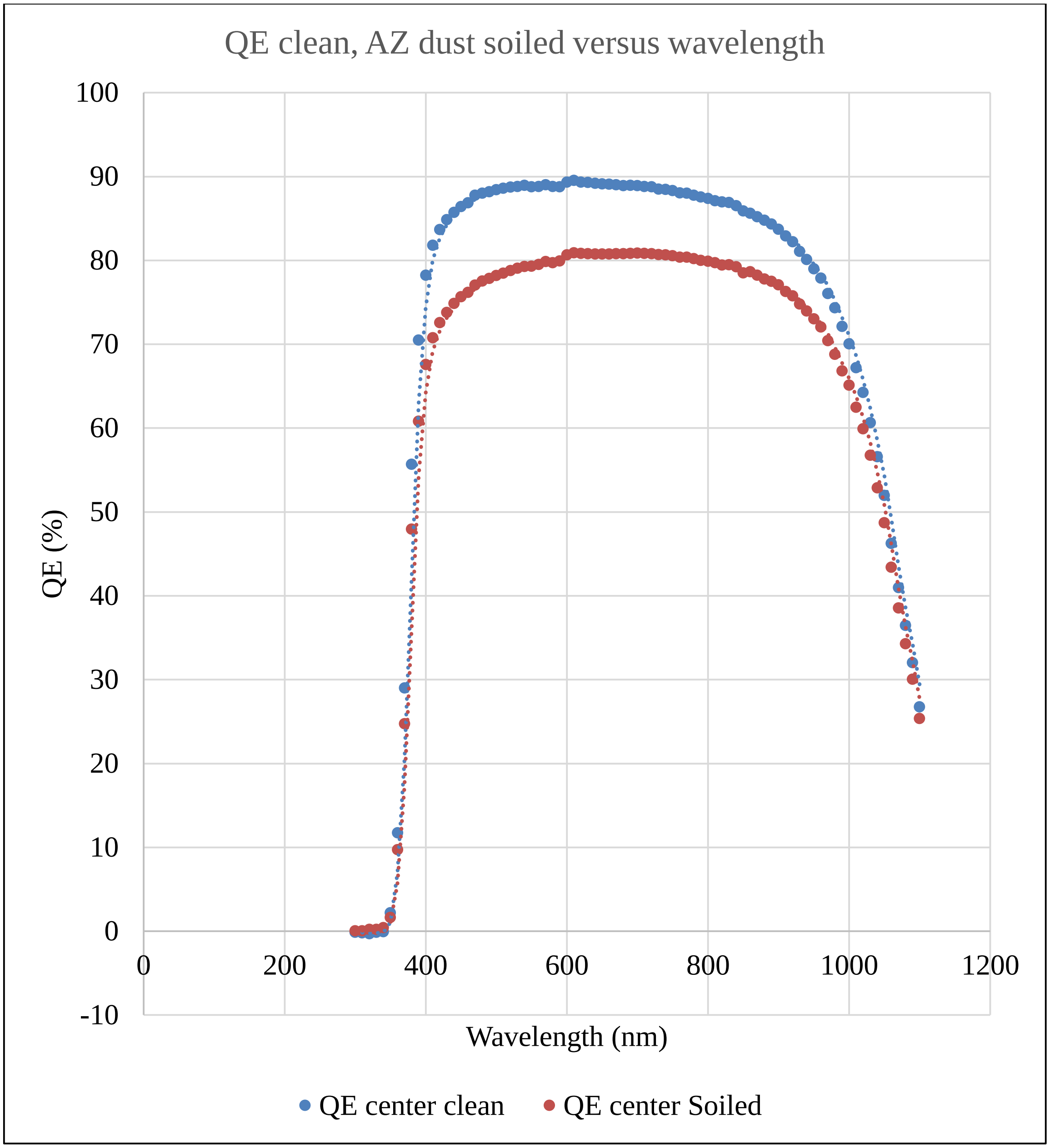

Figure 55 Sample Soiled with AZ Dust for 2 Cycles by the Dew Method Using Approximately 2 Grams of Sample Soil in the Soil Dispersion Chamber and Approximately 1 Minute Settling Time and Approximately 1.45 g/m^2 Soil Deposition Per Cycle

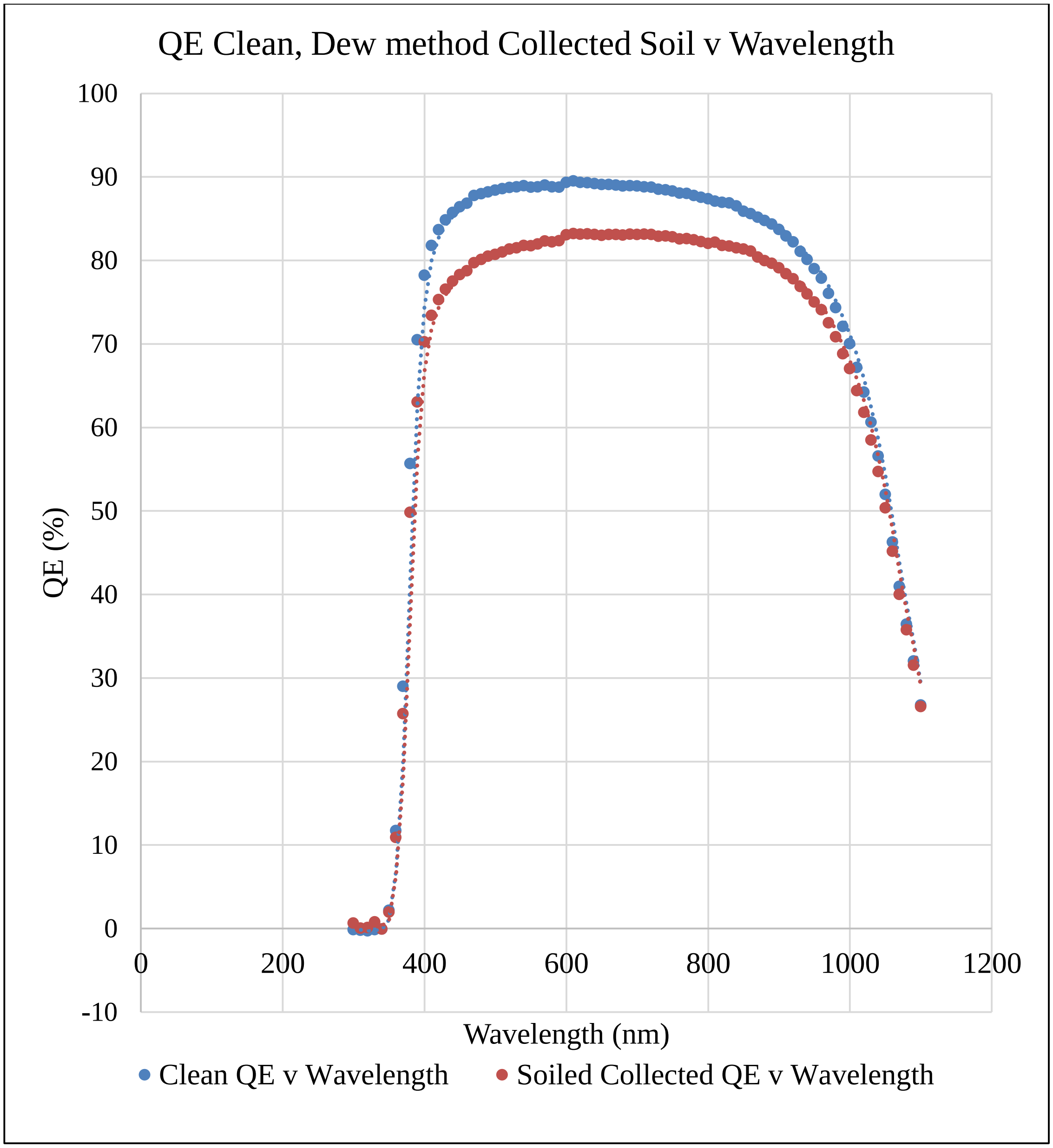

Figure 56 Sample Soiled with Collected Soil for 2 Cycles by the Dew Method Using Approximately 2 Grams of Sample Soil in the Soil Dispersion Chamber and Approximately 1 Minute Settling Time and Approximately 1.45 g/m^2 Soil Deposition Per Cycle

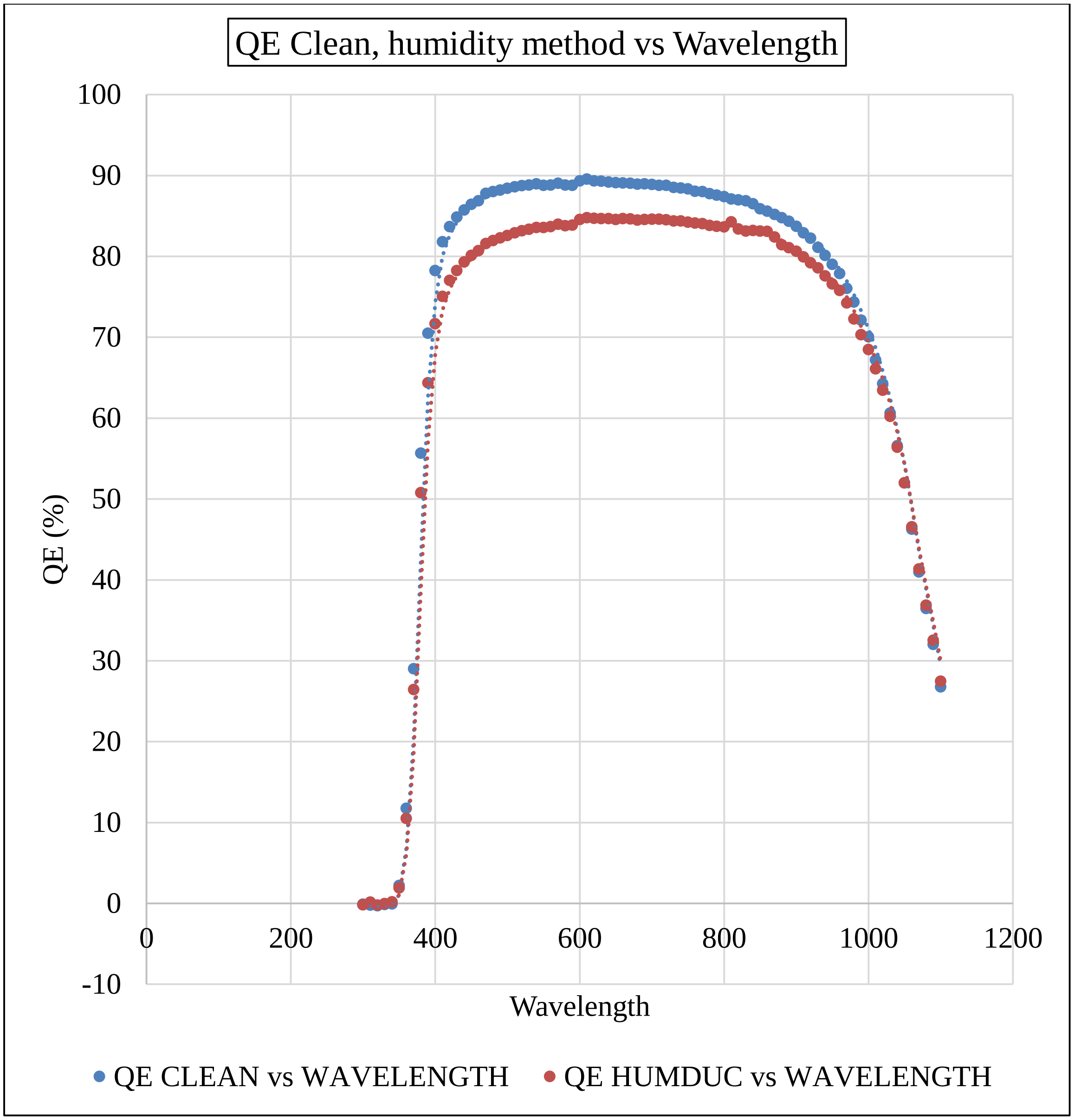

Figure 57 Sample Soiled with AZ Dust for 2 Cycles by The Humidity Method Using Approximately 2 Grams Of Sample Soil In The Soil Dispersion Chamber And Approximately 1 Minute Settling Time And Approximately 1.48 G/M^2 Soil Deposition Per Cycle

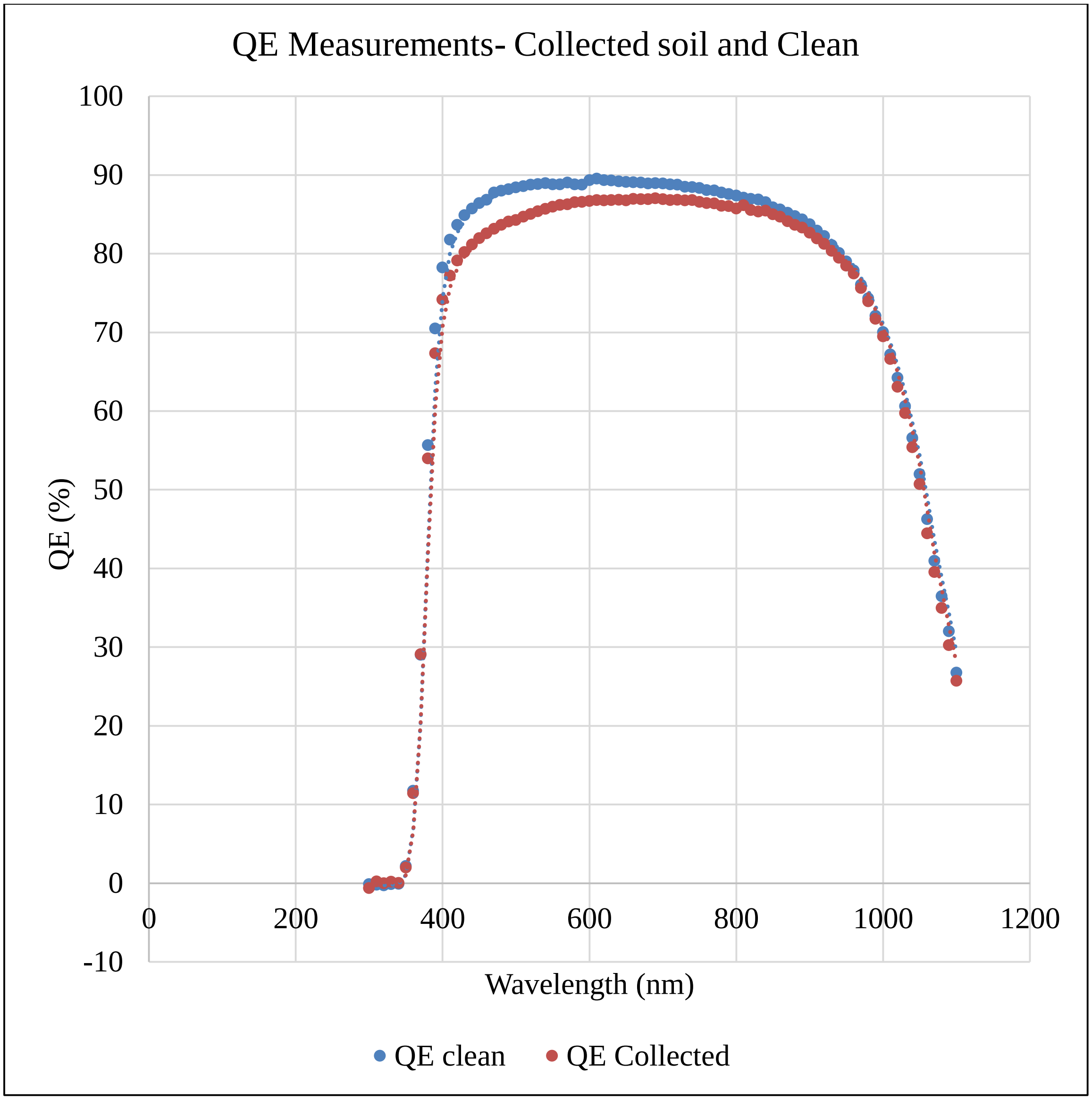

Figure 58 Sample Soiled with Collected Soil for 2 Cycles by the Humidity Method Using Approximately 2 Grams of Sample Soil in the Soil Dispersion Chamber and Approximately 1 Minute Settling Time and Approximately 1.48 g/m^2 Soil Deposition Per Cycle